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THE CONSTRUCTION OF THE HARLEM RIVER TUBES
A PORTION OF THE SUBWAY SYSTEM
IN NEW YORK CITY

BY

HOWARD Babcock GATES

A THESIS SUBMITTED FOR
THE DEGREE OF CIVIL ENGINEER

University of Wisconsin
1915

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SCOPE.

The purpose of this treatise is to present a general outline of the progress in sub-aqueous tunnel construction as applied to conditions in New York City, but with particular reference to a novel type of tunnel applicable to the crossing of shallow rivers such as the Harlem River. The basis of such a tunnel is formed by steel tubes constructed of light structural shapes which depend for their successful placing upon the absolute control of the hydraulic principles of buoyancy, and upon a mass of encasing concrete and a reinforced concrete lining for their strength and utility as a satisfactory subway structure. The essential details of such a method as carried out in the construction of that portion of the new subway system for New York City which crosses under the Harlem River and its comparison with a method previously used, form the subject matter of this thesis.

HISTORICAL.

The art of tunneling has been known and practised since very ancient times, the developement of its essential principles antedating most of the engineering structures of today. The first tunnels of which there are any existing records are those built by Shalmaneser II (860-824 B.C.), but the Romans doubtless rank as the greatest tunnel builders of antiquity in the number, magnitude and useful character of their works, and in the development of methods. Their introduction of inclined galleries and shafts allowing work to be prosecuted at various points and the breaking up of rock by heating and the sudden cooling with water (or vinegar in calcarious rock), together with the almost unlimited numbers of slaves and prisoners of war available for this work, is accountable in a large measure for their progress.

The introduction of gunpowder gave a strong impetus to tunnel building as a commercial and public utilitarian construction, culminating in the building of the Mount Cenis tunnel in Europe and the Hoosac tunnel in America and establishing the utility of machine rock drills, air compressors and high explosives fired by electricity.

With this progress in hard ground or rock tunnels the art of soft ground and sub-marine tunneling made comparatively little progress until the invention and use of the shield by Sir Isambard Brunel in excavating a tunnel under the River Thames in London, which was begun in 1828 and finished in 1843. Peter William Barlow in driving the second tunnel under the Thames in 1869 used iron lining in connection with a shield and from these inventions has grown the shield method in its practical and satisfactory developement as we know it at present.

The first application of the shield to tunneling in America was made in 1869 in a short piece of tunnel built under Broadway in New York City by use of a shield designed by A. E. Beach and claimed to be the first to make use of hydraulic pressure to force the shield forward. The original franchise for the project contemplated the construction and operation of a pneumatic tube 8 feet in internal diameter, beginning near the Post Office at Warren Street and extending northerly under Broadway presumably for the transportation of mail, parcels and light freight. Altogether 250 feet of this tunnel was constructed, 200 feet of it being on tangent and lined with brick and 50 feet being constructed on a curve and built of light cast iron segments. In 1912 during the construction of a portion of the Broadway-Lexington Ave. subway, this tunnel was unearthed and removed and the shield was found intact except for some wooden

parts which had rotted away. An experimental car designed to fit the interior with very little clearance was also found in the finished tunnel, bearing out the report that there had been a practical demonstration of the scheme. The terms of the original franchise were modified from time to time until they included the right to build and operate by compressed air, a two track passenger subway of rectangular cross section extending as far north as 42nd. Street with branches under the Hudson River to New Jersey. The impractability of a pneumatic tube for the transportation of passengers was fortunately demonstrated before any further work was done.

The first sub-aqueous tunnel attempted in New York City was started in 1879 at the Jersey end of what is now known as the Mc Adoo or Hudson and Manhattan up-town tunnels. Dewitt C. Haskins proposed to tunnel the Hudson River silt by the aid of compressed air, using painted canvas laid upon the river bed to prevent the escape of the air, believing that the air would then support the silt forming a covering beneath which, the tunneling would be easily done. The method was tried but following accidents of lesser importance an in rush of mud and water occurred and several lives were lost causing the practical abandonment of the scheme. A pilot tube method was then devised for continuing the work. This consisted of building a small tunnel about 6 feet in diameter along the axis of the larger one and lining it with plates bolted together at the edges and working from 50 to 60 feet in advance of the full sized tunnel. The excavation was next carefully removed to the desired size and lined with thin plates supported by radial struts from the pilot tube after which a brick lining was built forming the completed structure. As the full section advanced the plates of the pilot tube were unbolted and reassembled

at the advance face. After many vicissitudes, Haskin was obliged to stop work in 1888 having completed about 2700 of the 11,560 feet contemplated, but he had demonstrated the success of compressed air support. He was the first to use compressed air in any important tunnel and believed the idea to be original with himself but this appears to have been erroneous for a compressed air system for this purpose had been patented in England by Admiral Cockrane 50 years before. The following year the enterprise was taken up by English contractors and work resumed by the shield method, marking the first application of the shield to sub-aqueous tunneling in this country. Owing to a shortage of funds this work was interrupted again after a progress of 1700 feet had been made and nothing further was attempted until 1902 when the Railroad Company was reorganized and under the management of Wm.G. Mc. Adoo the tunnels were completed.

The successful application of shield methods to the exceptional hazards of tunneling the Hudson River silt together with the most urgent demands for additional rapid transit facilities to the contiguous and suburban communities of New Jersey, Long Island and The Bronx, is accountable for the remarkable progress made between the years of 1902 and 1908 during which time 14 shield driven single track tunnels having a total length of 16.8 miles were completed across the Hudson and East Rivers. The conditions of depth of water, strong tides and the uncertain and varying materials encountered, gave to each of these projects serious problems which demanded the highest order of engineering skill and the expenditure of immense sums of money to successfully overcome.

HARLEM RIVER TUNNELS.

In the inception of this progress in shield driven tunnels, there arose a problem of constructing a two track crossing under the Harlem River to form the connecting link in the presently operated subway systems of the Boroughs of Manhattan and The Bronx. The Harlem River is only about 400 feet wide and 20 feet deep at the point of crossing which warranted the consideration of using a shield as a consequence of which, a new and untried method was evolved and with alterations, proved to be successful and decidedly more economical than the shield method could have been. Owing to the fact that the Harlem River Tubes which form principal subject of this treatise were constructed to satisfy so nearly the same conditions, being under the same river and about three quarters of a mile to the east, the details of this first structure will be left until later to afford a better comparison of their respective merits.

The Harlem River at the point of crossing of the Lexington Avenue subway (i.e. from E. 132nd. St. and Lexington Ave. to E. 135th. St. and Park Ave.) is almost exactly 600 feet between pier or bulkhead lines and varies in depth from 20 to 26 feet, being 23 feet on the average below mean high water. Preliminary wash borings indicated that there was from 10 to 15 feet of alluvial silt or soft mud overlying clay or sand but no rock within the designed limits of the structure excepting a small amount at the extreme south end along the west side. This practically settled any consideration of the use of shields for this work because it would have been necessary to blanket such a bottom with from 10 to 15 feet of clay in order to retain the air pressure, which on account of the shallow channel would not have

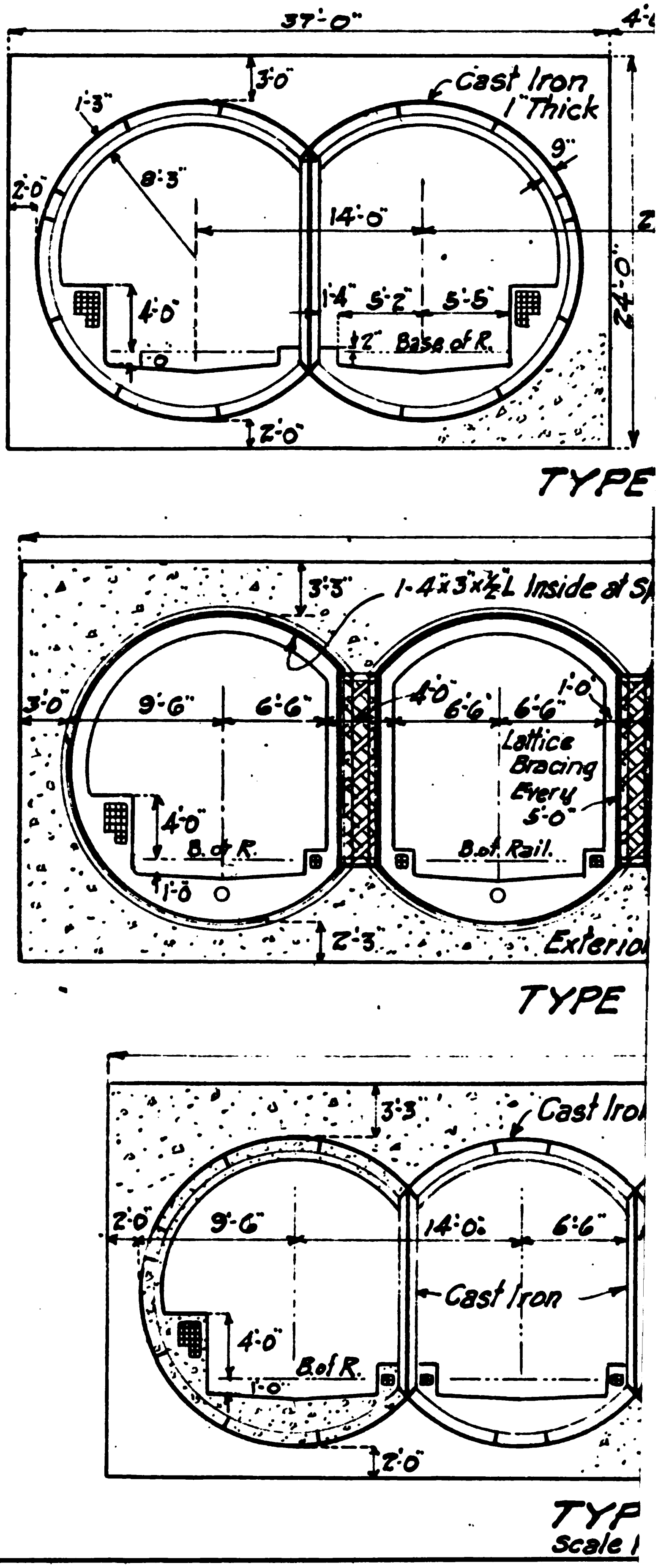

Figure 1

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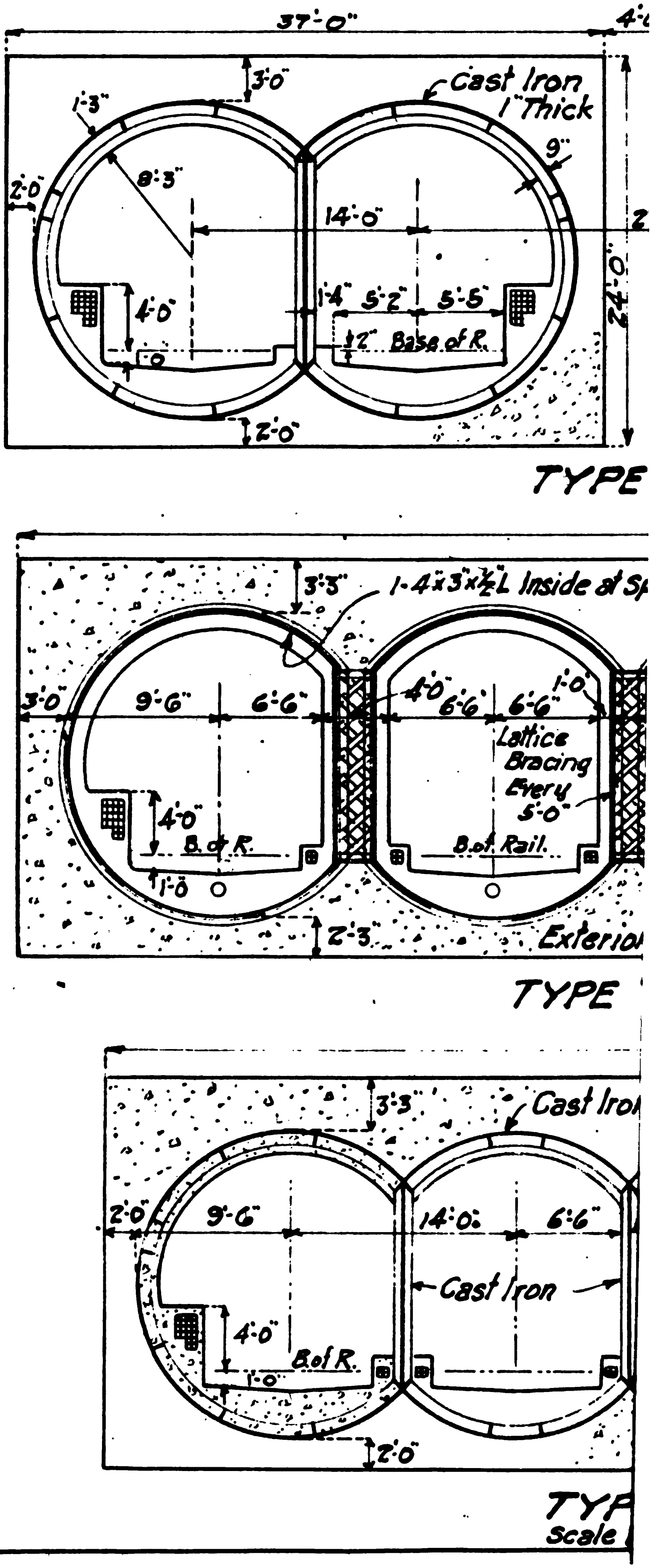

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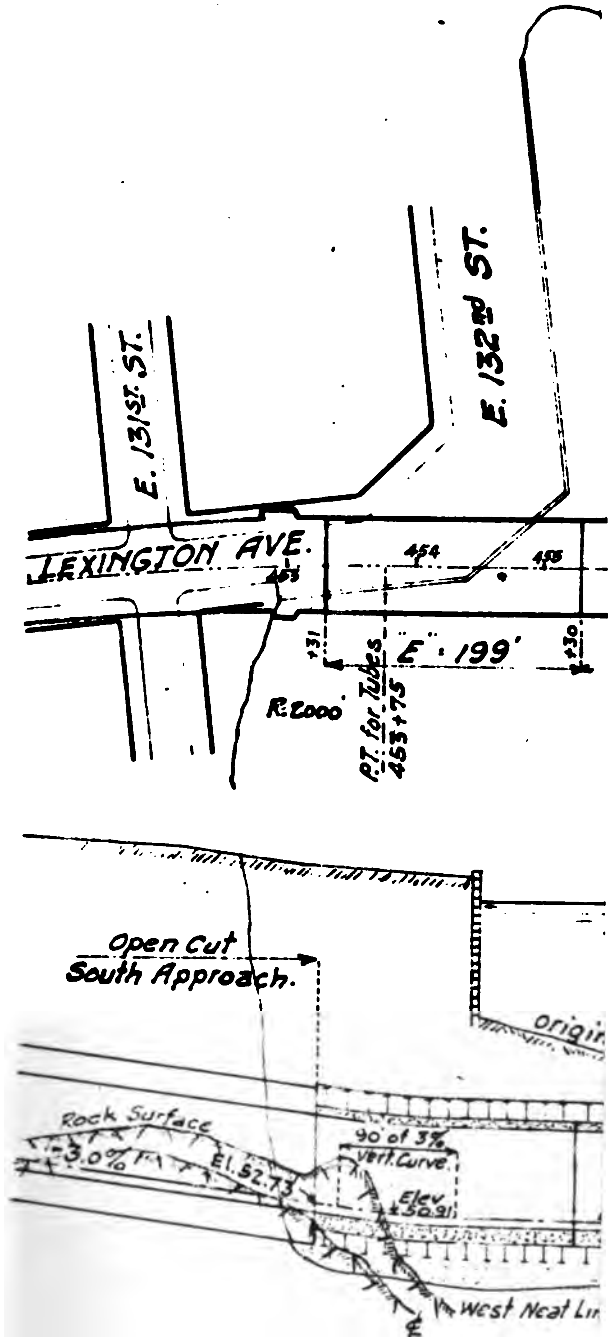

Figure 2

nel is entirely on tangent and passes under the river channel c

been permitted without dredging out an equivalent amount of the original bottom. The magnitude of the work would scarcely have justified the expense of the shield method except as a last resort even if there had been no other considerations, and the completion of the first crossing of this River followed by other tunnels built under similar conditions, was ample evidence that more economical and just as satisfactory methods were past the experimental stage.

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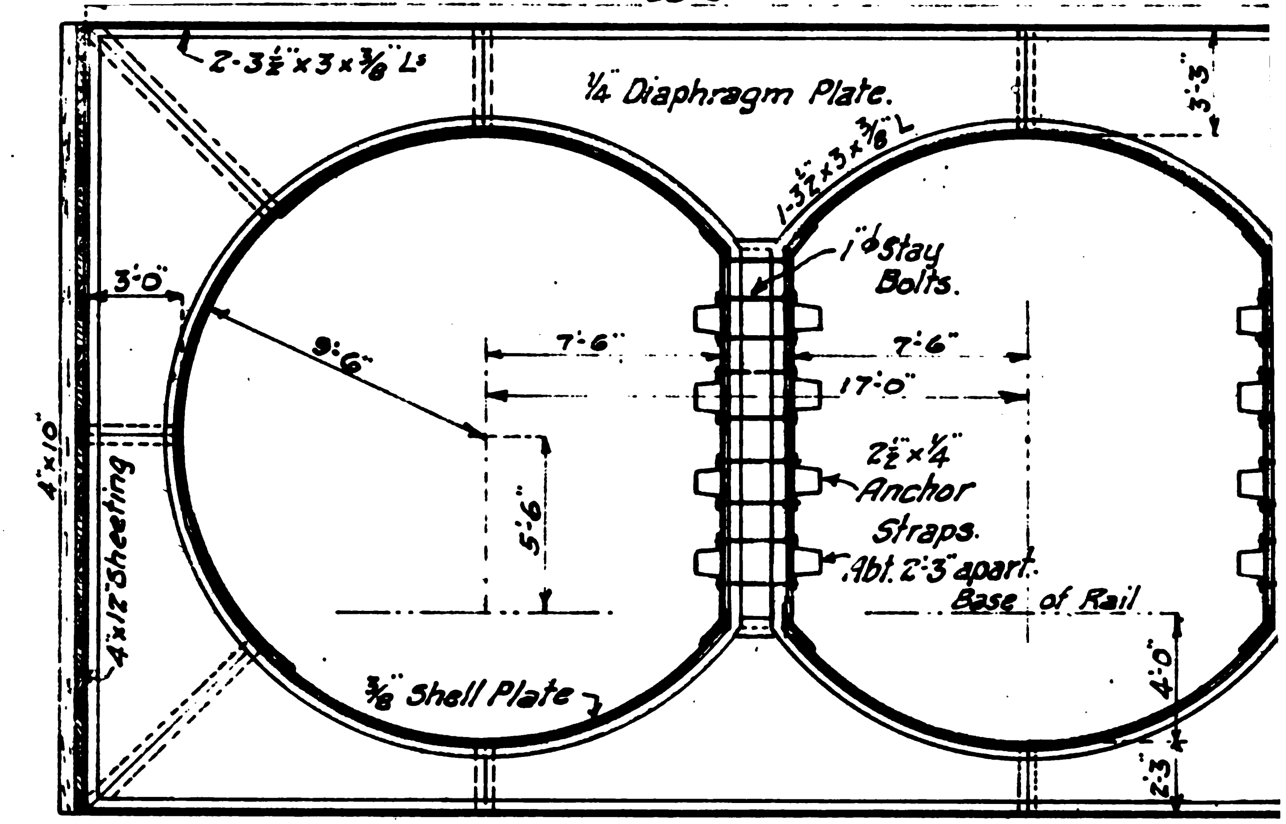
For the purpose of attracting bids from contractors on as equitable a basis as possible, it being realized that if the type and methods of construction were rigidly defined certain existing patents claiming to cover such methods would practically eliminate competition, three alternate designs were prepared to include the general principles but none of the details of successful types. Figure No. 1 shows the essential details of the three types bid upon and which were designated by the letters "H","K" and "L". The lowest bid for any of the types was $1425 and supposedly for type "L". However as the contract was awarded to the lowest bidder for the entire Section and as type "K" ~~being~~ was favored by this bidder, it was adopted at a price of $1500 per lineal foot and was let to Arthur McMullen and Olaf Hoff, July 22, 1912. Mr Hoff was connected with the two track Michigan Central Railroad tunnel work under the Detroit River at Detroit, Michigan and holds certain patents covering this type of construction.

DESCRIPTION OF TUBES AND METHODS.

Figure No. 2 shows in plan and profile the location and general alignment of the tubes. Except for a horizontal curve of 2000 foot radius about 40 feet long at the south end, the tunnel is entirely on tangent and passes under the river channel on a

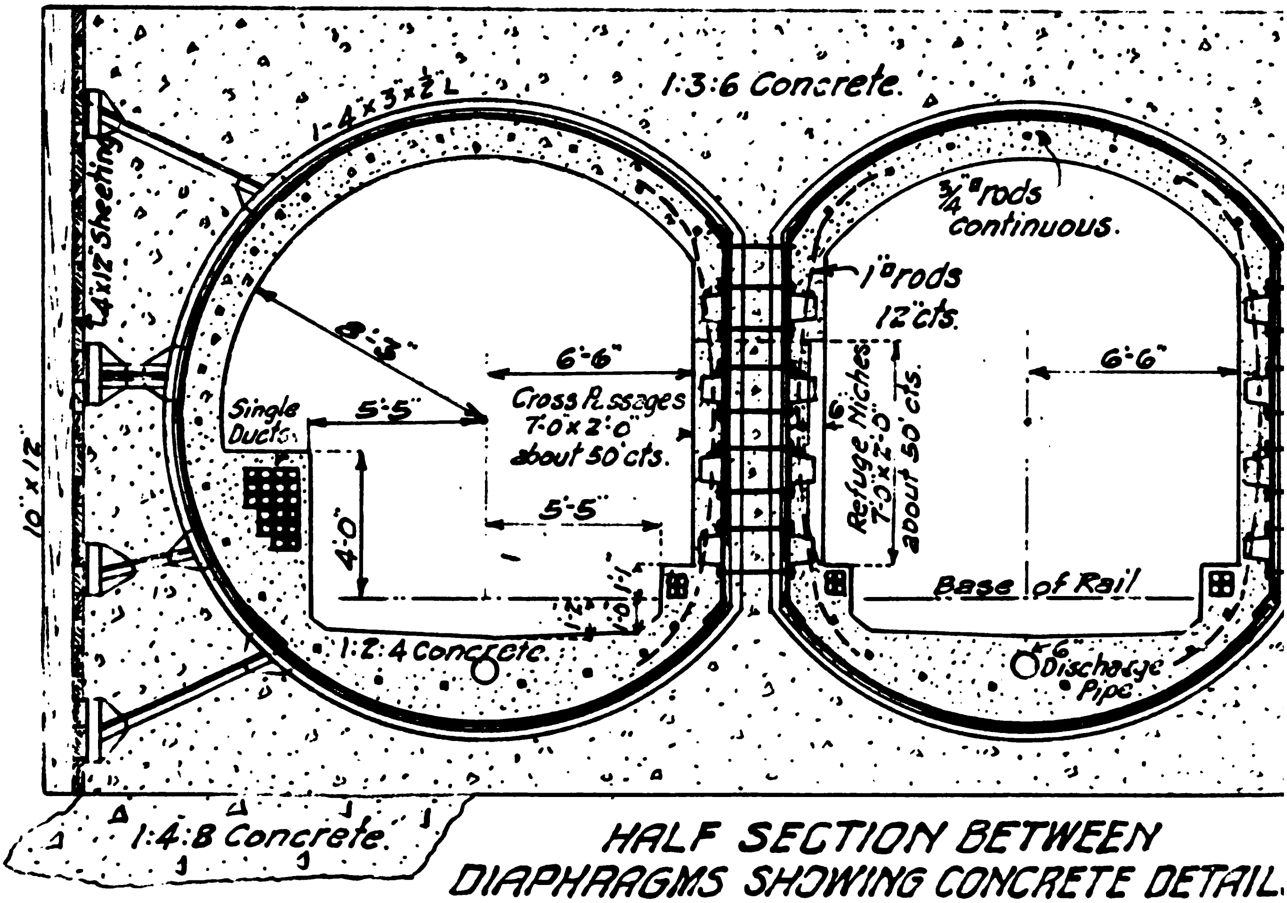
0.3 % grade with 3 % grades on the approaches. The steel portion of the structure consists of four parallel tubes 17 feet on centers having internal diameters of 19 feet with flat sides on their interior walls. The tubes are fastened together and held in position by 1-inch stay bolts spaced 27 inches on centers in each direction and by vertical diaphragm plates ¼ inch in thickness placed at right angles to the direction of the tracks at intervals of 15 feet 7 inches. These diaphragms conform to the outside dimensions of the tubes and are stiffened along their outside edged by two light angles. The addition of these diaphragms to the contract drawing requirements was the most important change made in adapting type "K" to the contractors plans. The change from the lattice bracing at 5 foot intervals to the stay bolts between the intermediate walls, was made to give greater rigidity and incidentally provided a ready method of attaching the anchor straps for the bonding of the inside concrete sidewalls to the steelwork. The reinforcing rods which were added,were not considered absolutely necessary but they were used to give an additional factor of safety. These changes added 206 tons of structural steel and 180 tons of reinforcing rods to the original contract drawing requirements. All of the tube plates and most of the angles were three-eighths of an inch in thickness and the structural steel for the four tracks had an average weight of 5600 pounds per lineal foot.(See Figure 3 for adopted Section).

For convenience of erection and placing, the tunnel was divided into five sections referred to as Sections A, B, C, D and E, and they were built and lowered into position in this order. Sections A, B, C and D are each 220 feet long and Section E which is the southernmost section and the last to be placed, is 200 feet long making the total length of the tunnel 1080 feet.



HALF SECTION AT DIAPHRAGM SHOWING STEEL DETAILS.

Symmetrical about this line

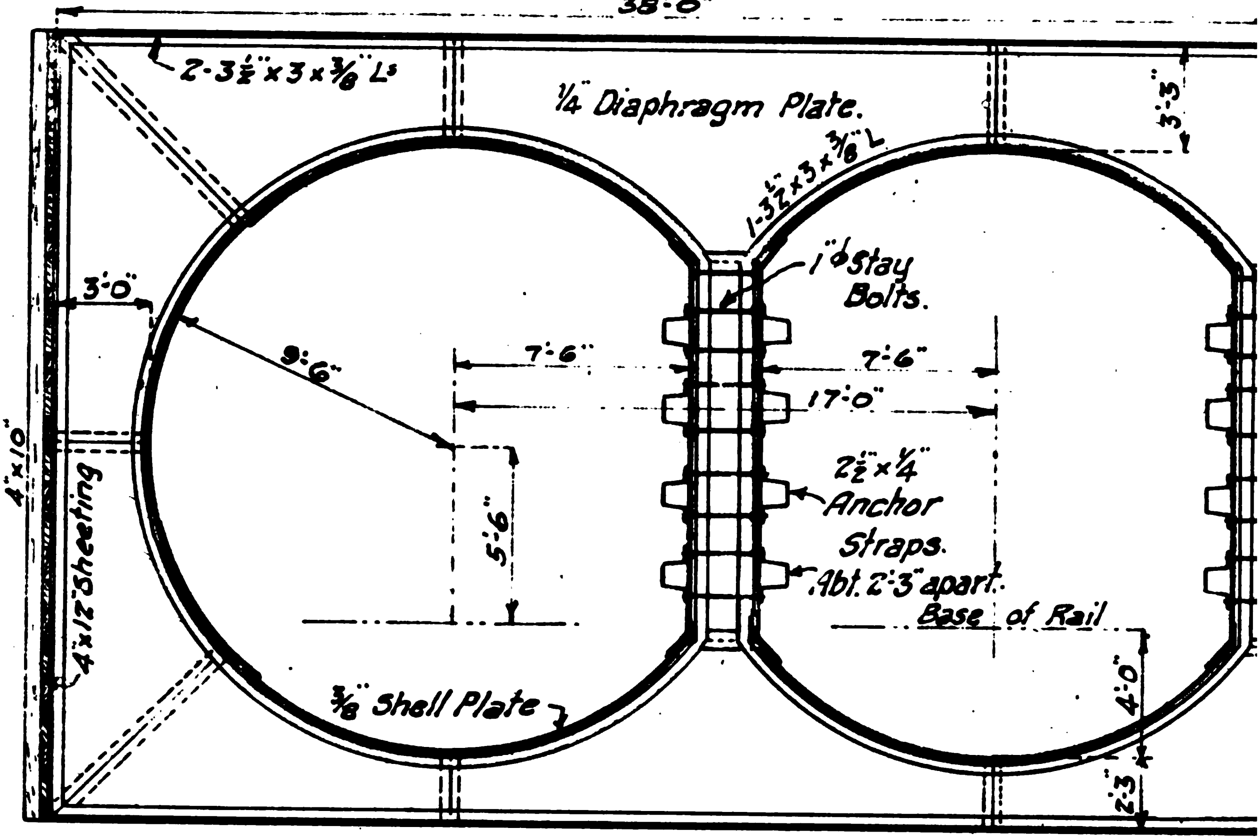


HALF SECTION BETWEEN DIAPHRAGMS SHOWING CONCRETE DETAIL.

Scale 1" = 6'-0"

Figure 3

(barge measurement) and was sublet to a dredging company at $.



HALF SECTION AT DIAPHRAGM SHOWING STEEL DETAILS.

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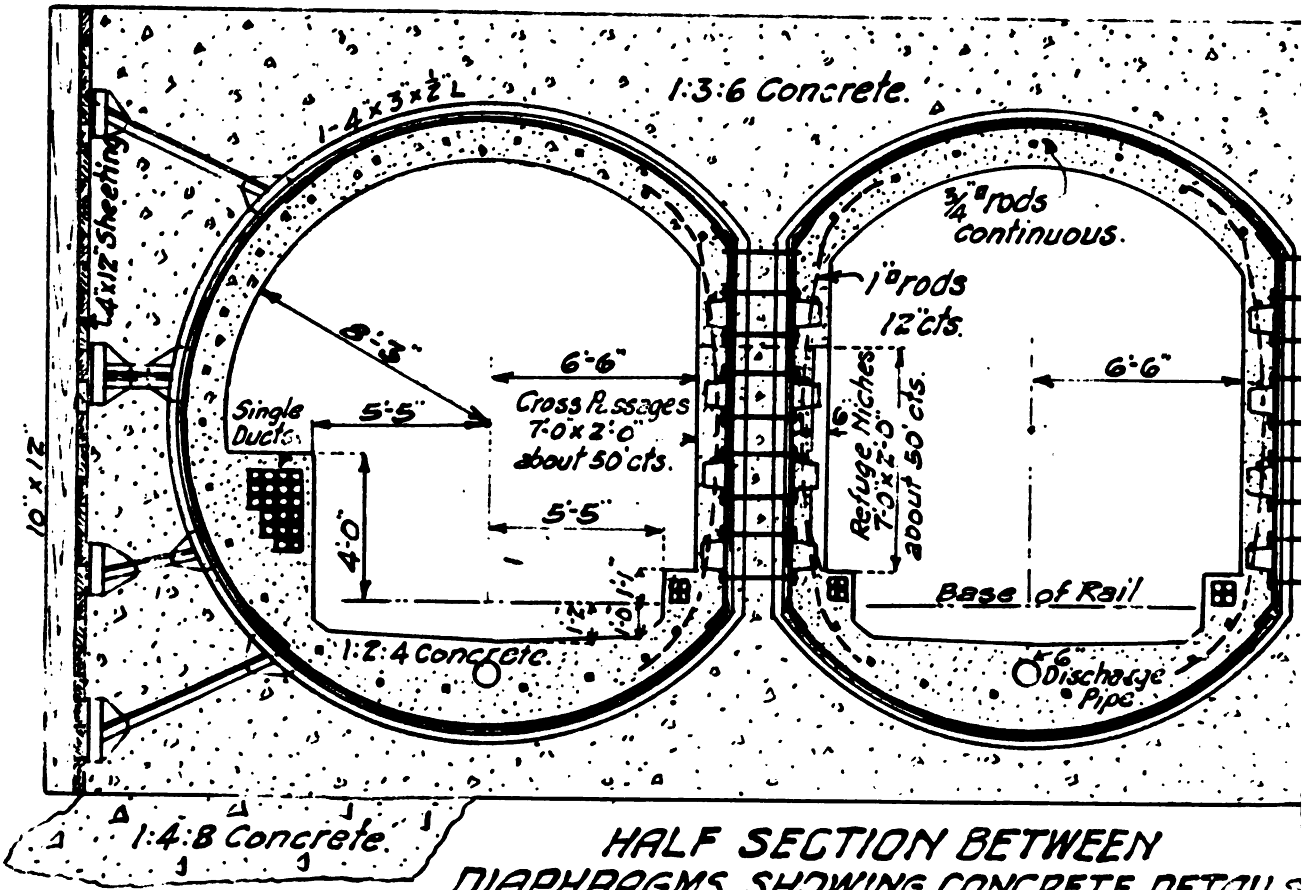

HALF SECTION BETWEEN DIAPHRAGMS SHOWING CONCRETE DETAILS

Scale 1" = 6'-0"

Figure 3

(barge measurement) and was sublet to a dredging company at $.5

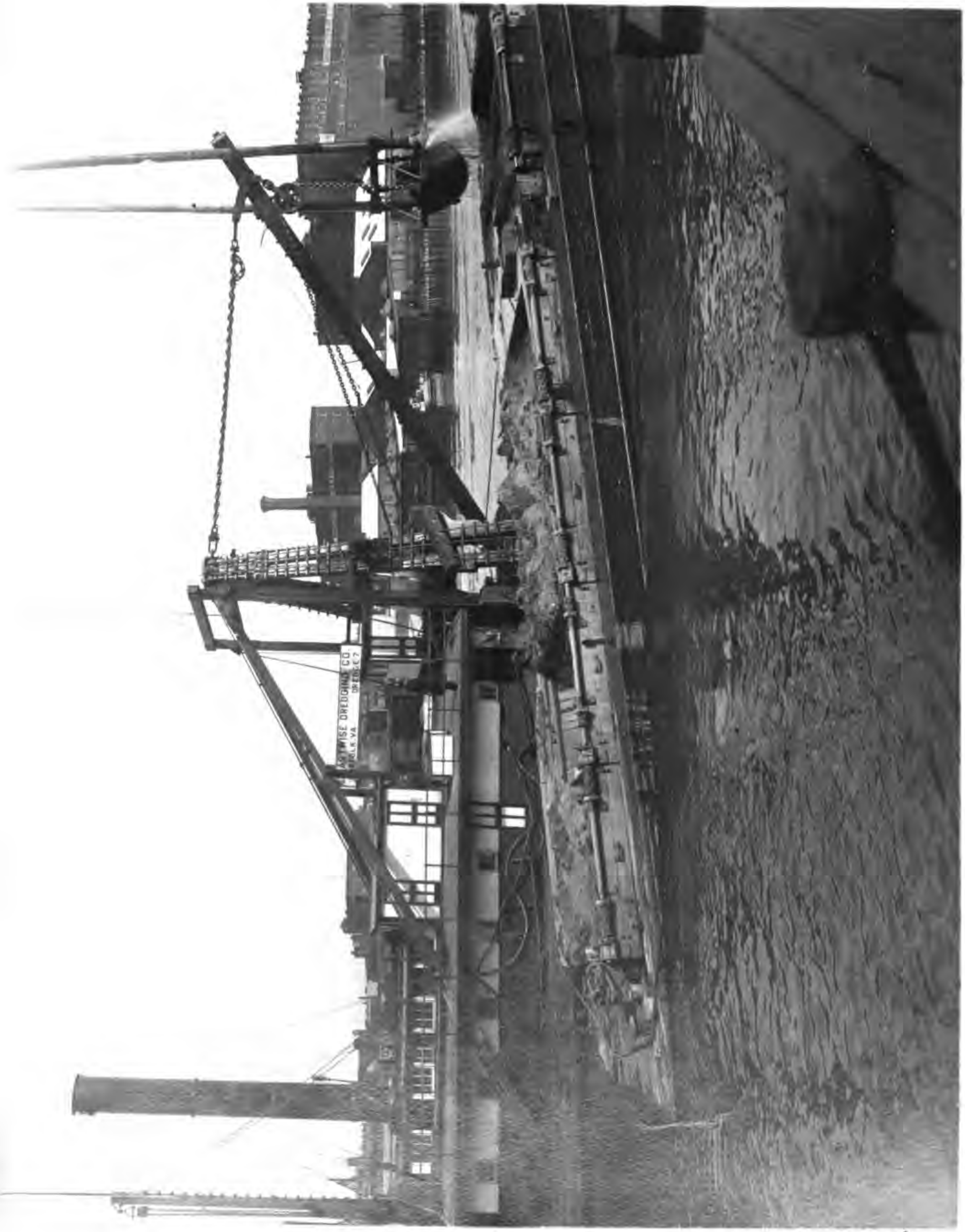

Figure 4

(barge measurement) and was sublet to a dredging company at

Clam shell dredge working in the south end of Section A

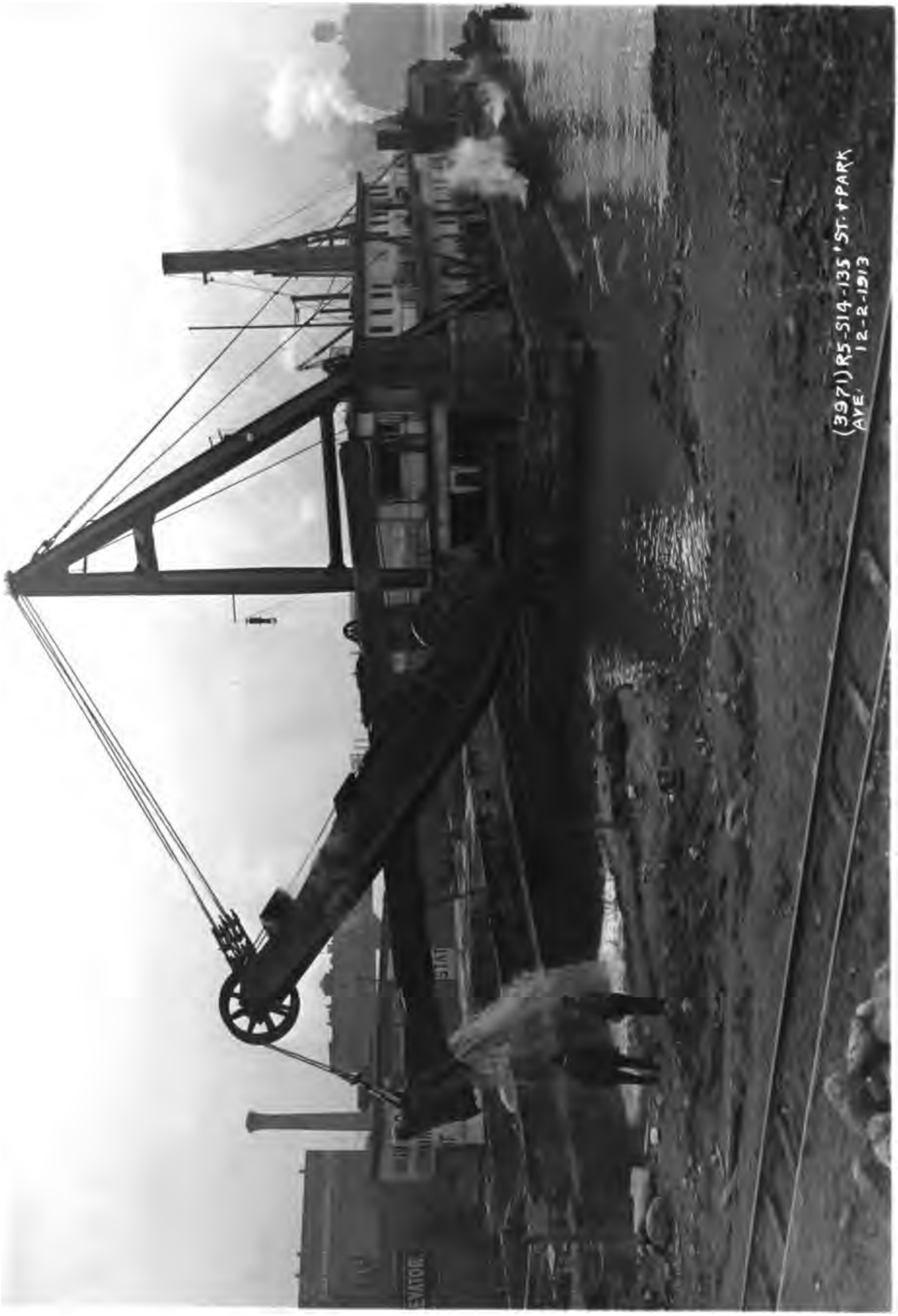

Figure 5

(barge measurement) and was sublet to a dredging company at

Dipper dredge working in the north end of Section D,

in rock fill and boulders.

In order to comply with the requirements of the Secretary of War, it was necessary to cross the River at such a depth that the top of the tunnel should not be less at any point between the established bulkhead lines than 30.7 feet below mean high water. The tunnel was placed as near to this limit as possible making the top of the finished structure an average of 7 feet below the original river bed and the lowest point in the structure 57 feet below mean high water. In order to avoid some of the expensive and rather dangerous approach work, the tunnel was projected about 120 feet landwards on the Manhattan side and 360 feet on the Bronx side, Section D being entirely a land section.

Briefly the method was to construct the steel tubes, attach wooden forms continuously along the sides, launch the section and after towing it to and anchoring it above the designed location, gradually lower it into a previously previously prepared trench. By means of tremies, concrete was then deposited around this steel form and when a series of sections were in position and properly connected with the extreme ends bulkheaded, the water was pumped out and the interior lined with concrete. The function of the steel structure is to serve as a waterproofing envelope and as a form about which a properly shaped working chamber can be cast and through which a concrete tunnel can be built, designed to have sufficient strength independent of the enveloping steelwork and concrete, to make a safe structure. The various steps in order of proceedure will now be described.

PREPARATION OF TRENCH.

The dredging operations were started on March 10th.,1913 and completed on September 9th., 1914, removing 275,226 cubic yards (barge measurement) and was sublet to a dredging company at $.50

per cubic yard including the disposal of it. On account of the interruptions for the drilling and blasting of the rock encountered in Sections C and E, the above record gives no idea of the daily progress which averaged about 1300 cubic yards per 24 hours of actual working time including delays for minor repairs. For the greater part of the dredging work 4.5 yard clam shell buckets operated by dredges similar to that shown in Figure 4 were used, but where blasted rock and rock fill had to be excavated a 7 yard dipper dredge shown in Figure 5 was found to be more adaptable. All of the material removed from Sections A, B, C and D was loaded into scows and dumped at sea outside of the three mile limit, but that taken from Section E was used to backfill over the then completed sections.

The bed of the River through which the trench was dug, consisted of about 10 to 15 feet of a soft black alluvial deposit or silt overlying sand and clay with some gravel and a very few boulders. Throughout the excavated trench, the original foundation materials were very satisfactory and were found to be so compacted in places as to require persistant digging with a 4-ton - bucket in order to bring the trench to grade. The trench itself was made about 80 feet wide at the bottom, the materials being allowed to assume their natural slope which was found quite uniformly to be 1 on 2 in the river portion of the excavation. On the north side of the river, rock was encountered within the designed position of the structure and was removed by blasting. This work was sublet to a company equipped to do the work, for a price of $3.00 per lineal foot of drilled hole which also included the blasting. A steam driven drill mounted on a pile driver frame as shown in Figure 6 was used and 4-inch holes extending

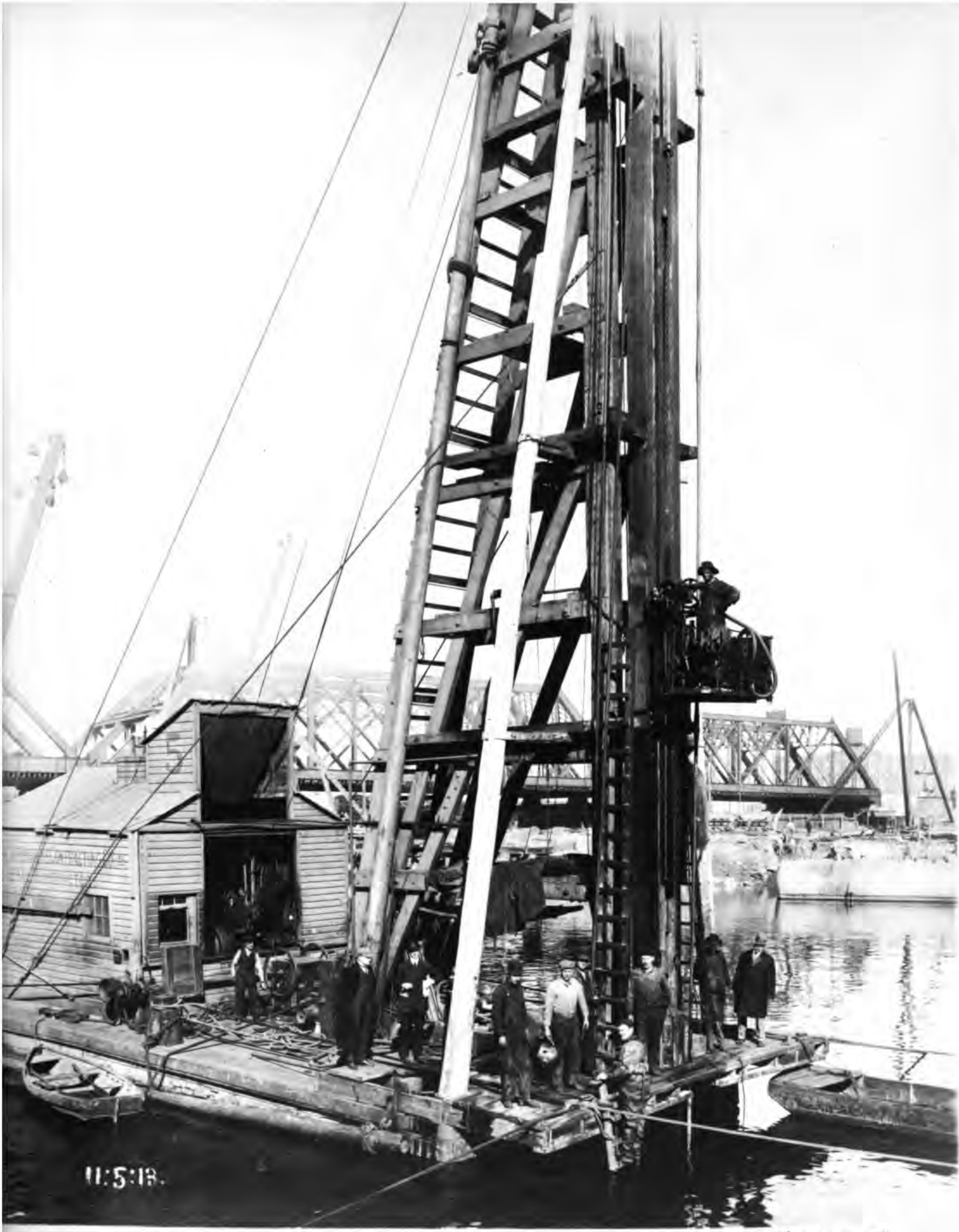

Figure 6

2 feet above high water upon which the steelwork for each Sect

Detail view of drilling apparatus. Diver ready to go down to load a hole preparatory to blasting.

feet into the rock and 60 feet below water were successfully drilled and the rock broken into pieces small enough to be removed by the dipper dredge. A small percentage of the holes drilled, filled with soft material from the side slopes and could not be loaded. In order to reduce this difficulty to a minimum, the holes were loaded and fired as soon after the drilling was finished as possible, the holes being loaded by a diver. They were spaced 5 feet on centers in each direction and were drilled 5 feet below the grade of the bottom part of the diaphragms to make sure that the rock should be removed clear of the structure. The average charge used was from one to one and one half pounds of 60 or 70% dymanite per lineal foot of hole. Later rock was also encountered in Section E extending over the southwesterly quarter of the Section and was removed by the same equipment and methods. That more rock was not indicated by the original borings can be accounted for by the fact that they were taken only along the westerly line of the structure and while it was expected that some rock might be found on the south side of the River, the borings on the north side taken at the west neat line, showed the rock to be about 20 feet below subgrade. It has since developed that the rock surface has an almost precipitious rise to the east and in the width of the structure (76 feet) rises from 20 feet below the subgrade to 30 feet above.

ERECTION AND LAUNCHING OF TUBES.

While the trench was being excavated the tubes were being assembled over a "slip" at 152nd. Street on the Bronx side of the Harlem River about a mile from the site of the work. Four longitudinal stringers supported by piles formed a staging about 2 feet above high water upon which the steelwork for each Section

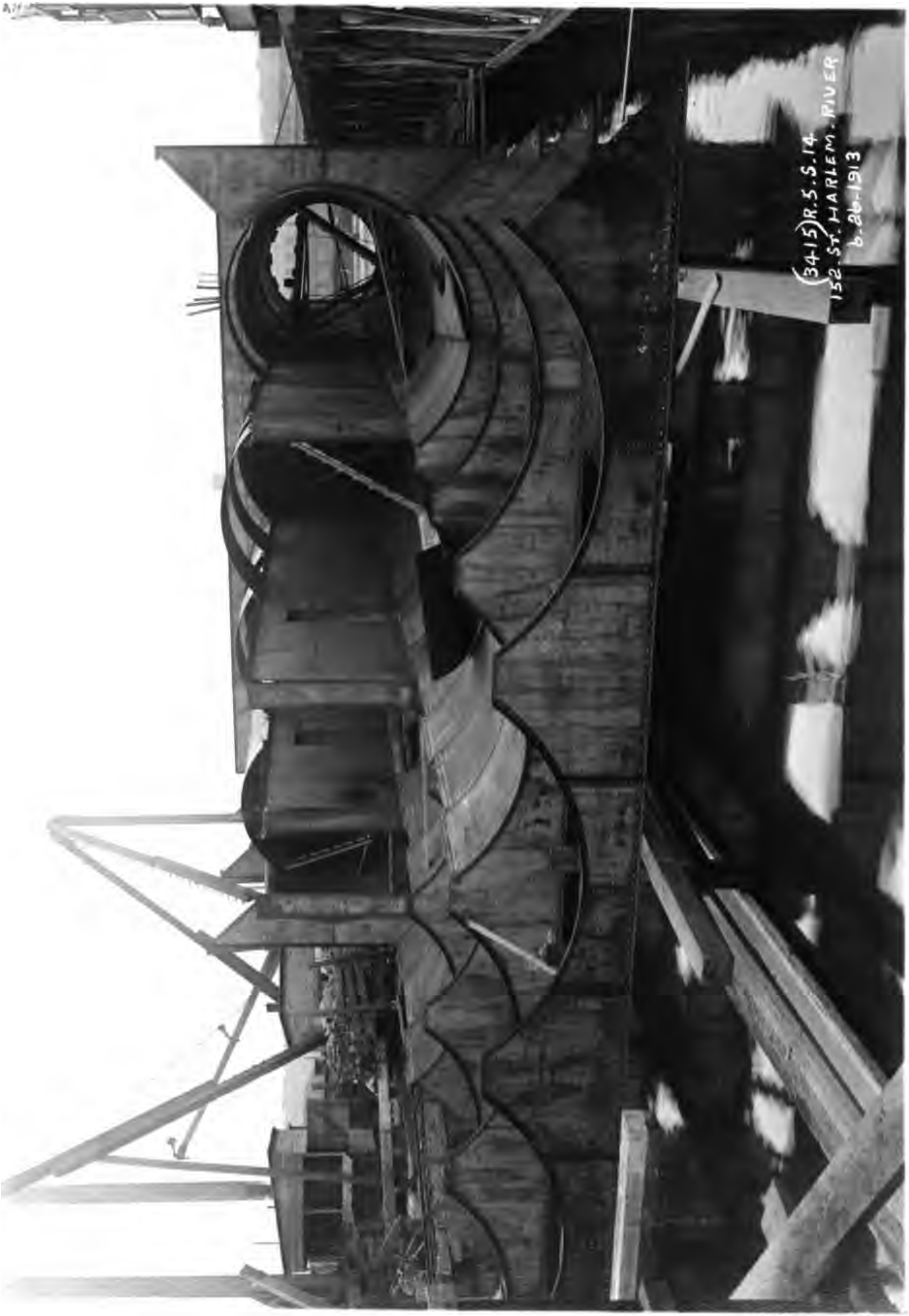

Figure 7

which was completed in 25 working days. The average cost of

Partially completed Section in "slip" at Contractors yard, showing order of assembling and longitudinal stringers resting upon piles and supporting the steelwork.

in turn was assembled and its equipment of bulkheads and sheeting practically completed before launching. The steel was fabricated by the American Bridge Company at their Ambridge plant and shipped on lighters to the erection yard in pieces which could be conveniently handled without liability to distortion. The cost of this steel delivered was $45.00 per ton.

The order of assembling was altered and improved after the first Section was built, the most advantageous scheme being to set and block the bottom portions of the diaphragms in position following with the placing of the invert, side and crown plates, omitting the alternate crown plates until the riveting and caulking were completed in order to obtain plenty of light for this work. Then the omitted crown plates were added and the top portions of the diaphragms finished. Figure 7 indicates this progressive order of assembling. Each 220-foot section required the driving of approximately 80,000 rivets, a gang of four men driving an average of 400 rivets in 8 hours with a maximum of 522. The tubes were made up of plates 8 feet in length making two lengths between each pair of diaphragms and requiring a stiffening angle to reinforce the joint at the lap. This angle was placed on the outside of the shell in order to leave a smooth surface on the inside for convenience in placing the concrete lining. Lap joints were made throughout, all seams being caulked in order to make a water tight structure. This work was satisfactorily accomplished by means of the ordinary caulking tools operated by riveting hammers. The average time for the complete assembling of the four 220-foot Sections was 30 working days with an average daily force of 80 men. The best time was made on Section D which was completed in 25 working days. The average cost of

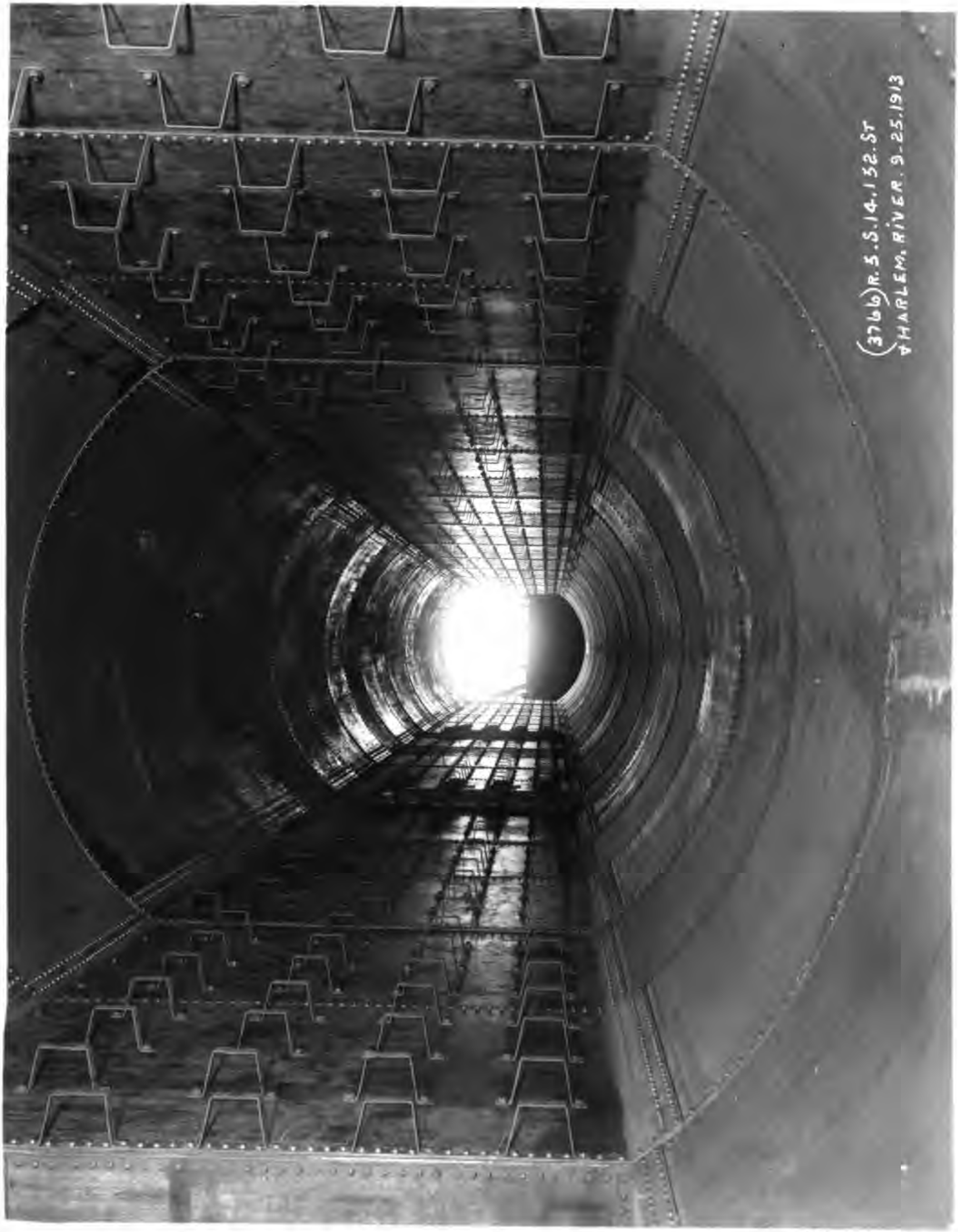

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Figure 8

View of one of the interior Tubes of Section B and showing partial end bulkhead. A portion of a cross passage appears in the foreground at the left of the view.

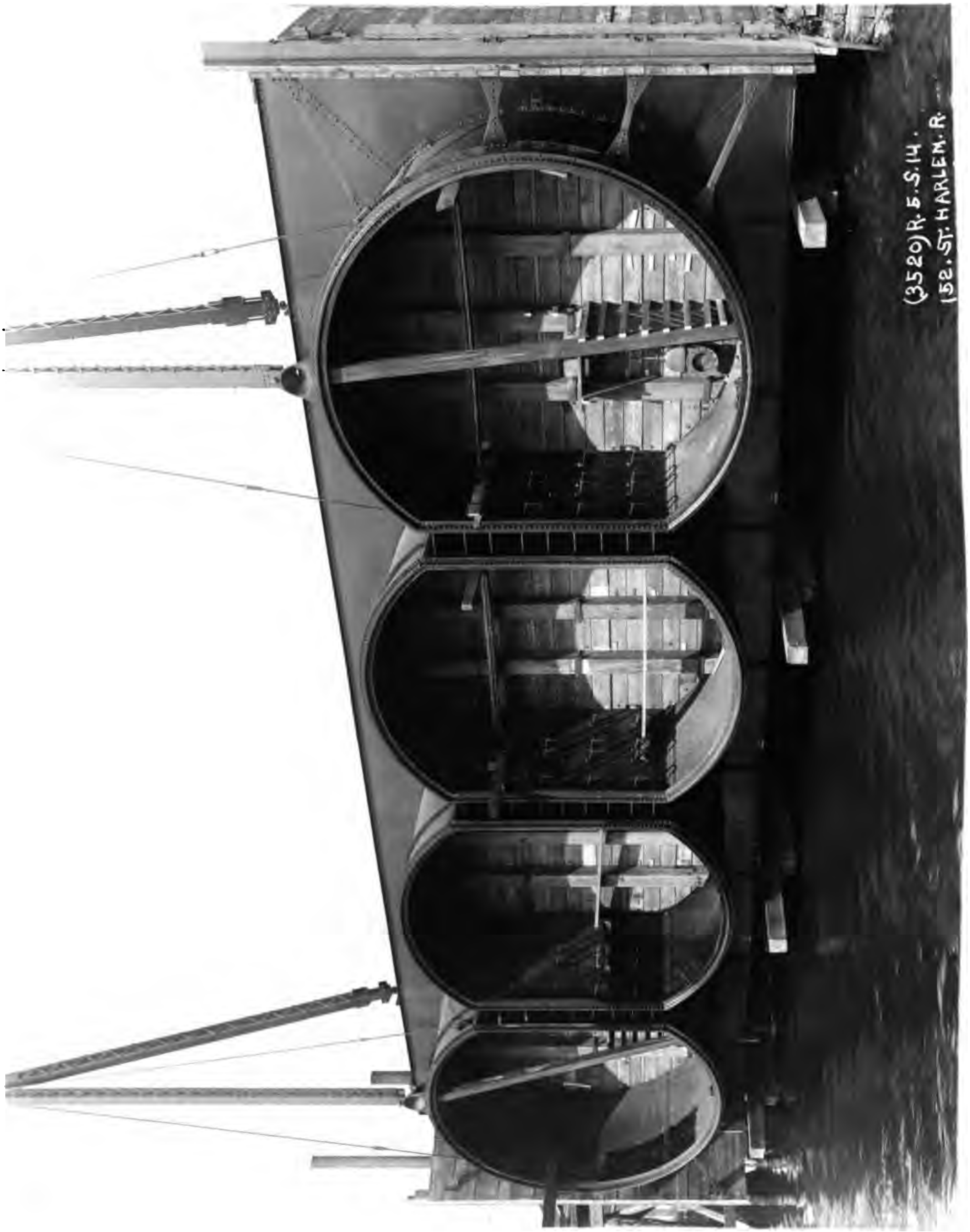

Figure 9

South end of Section "A" before launching with its full equipment of bulkheads, valves, masts etc.

this assemblig and erection including the caulking of the steel work was $20.00 per ton. Figure 8 shows an interior view of the completed steelwork. Before the Section was launched the alignment masts were plumbed and the targets set, the bulkheads completely assembled equiped with valves and ship caulked, and the wooden sheeting (which was assembled in panels) was bolted to the diaphragm stiffening angles. This sheeting was supported at the middle of its span by a 10" x 12" timber bolted to the radial angle struts attached to the reinforcing angles at the lap joints in the shell plates, as shown in Figures 3 and 9. The average cost of equipping the tubes with bulkheads, sheeting etc. was $5.00 per ton including the cost of the timber. This made the total cost of the tubes assembled and ready for launching including the overhead charges, $70.00 per ton.

The launching operation consisted of placing nine flat-decked boats uniformly spaced beneath the structure at low tide and allow ing the rising tide to lift the structure clear of its ways, trans fering the entire weight of the Section to these boats. By means of tugs the Section was then towed out into the River and valves in these boats were simultaneously opened filling them with water. The water in connection with stone ballast previously placed in them, overcame the buoyancy of the boats so that as the Section gradually settled down and floated, the boats were readily pulled from beneath the Section by means of tugs. The flotation of the Section was made possible by the wooden and water tight bulkheads at the end diaphragms of each tube and the structure when launched was practically a big boat drawing about 3 feet of water (measured from the invert shell plate) and weighing with its equipment, approximately 750 tons. Figures 10, 11 and 12 show three

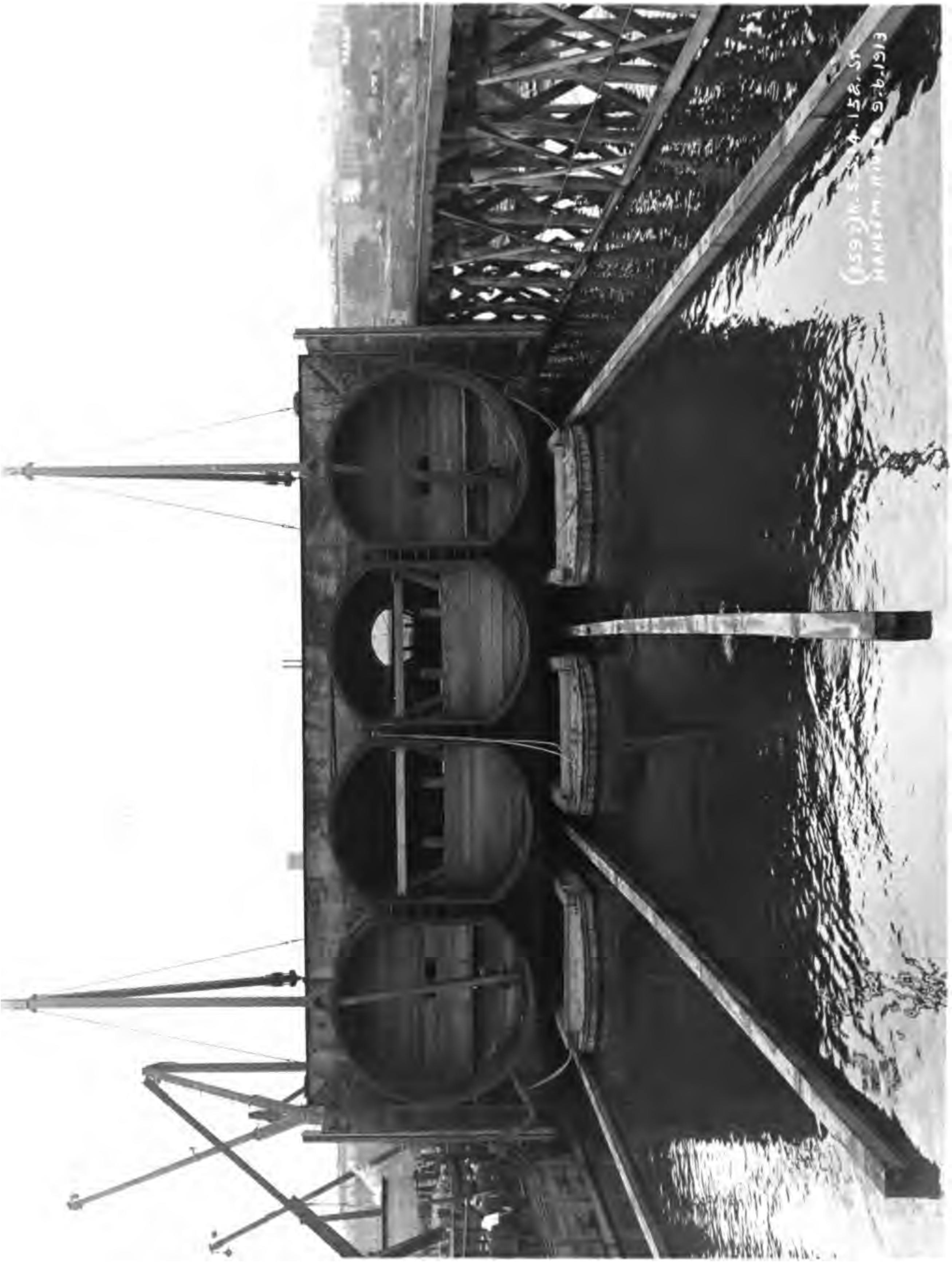

Figure 10

Section"B" placed upon flat boats and being towed out of the "slip".

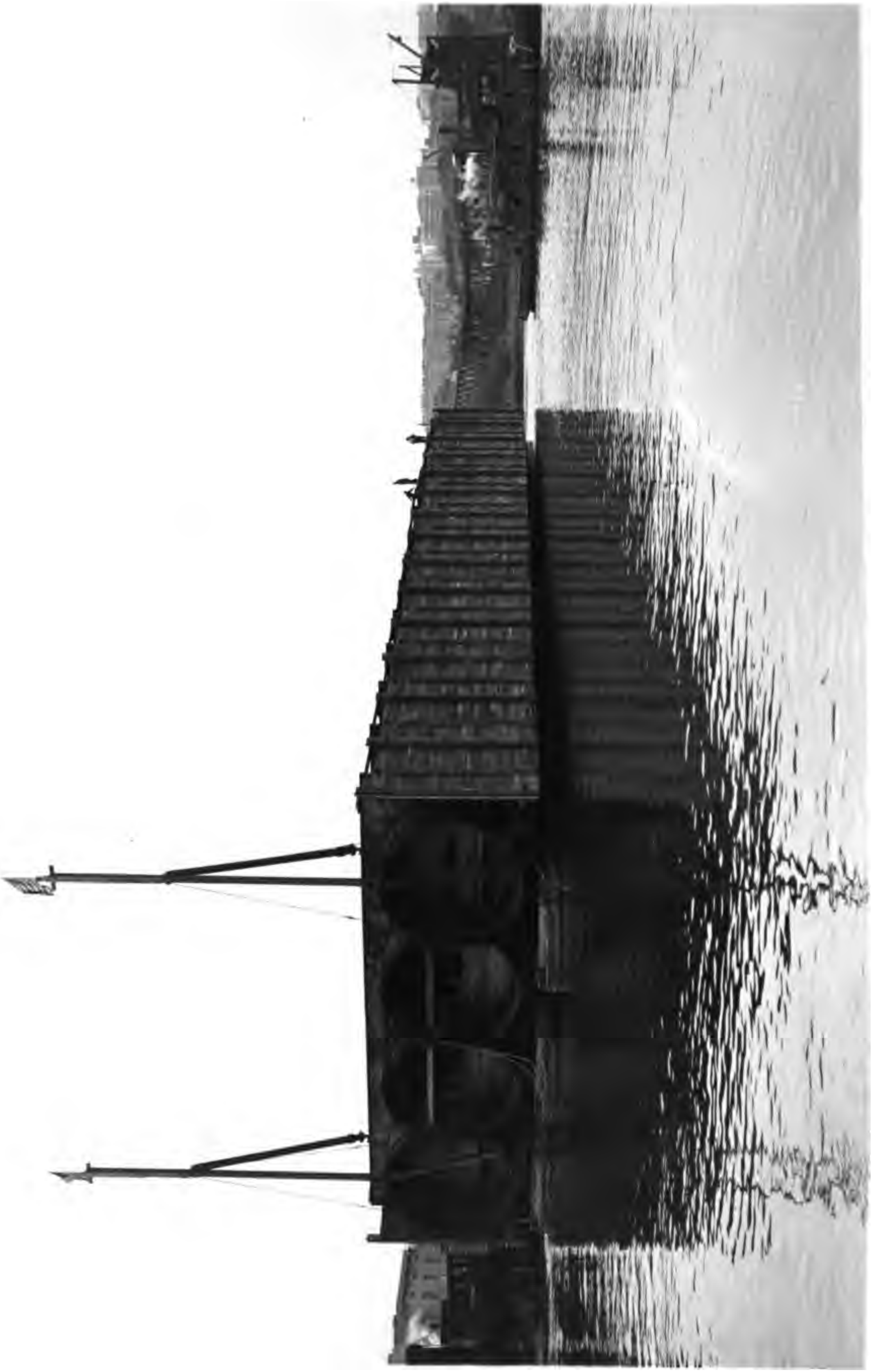

Figure 11

by wooden bracing and having a timber about 40 feet long fast

Section "B" after being towed out of the "slip" in process of being turned partially around before launching.

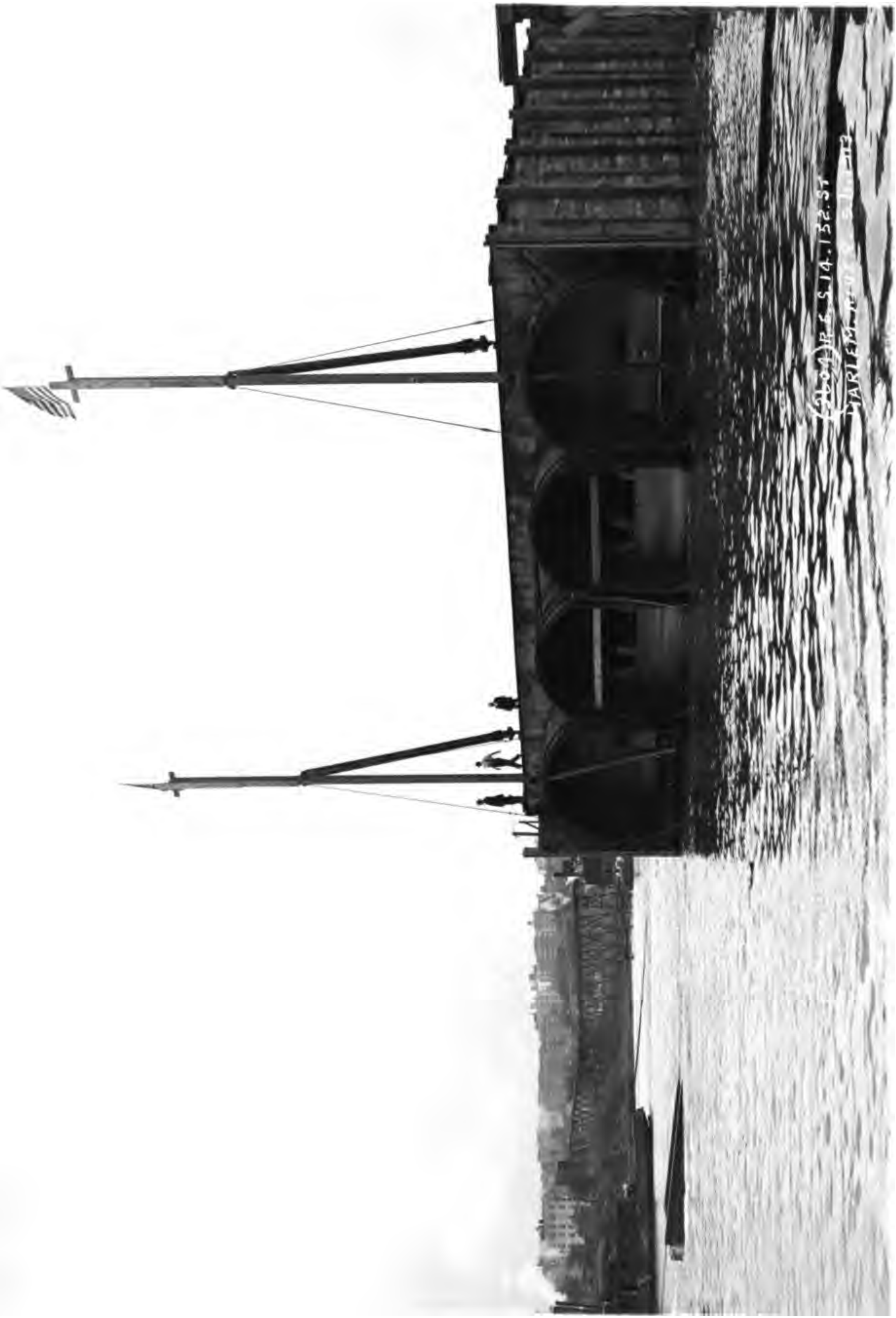

Figure 12

by wooden bracing and having a timber about 40 feet long faste

Section "B" after being launched, showing flat boat being pulled from beneath .

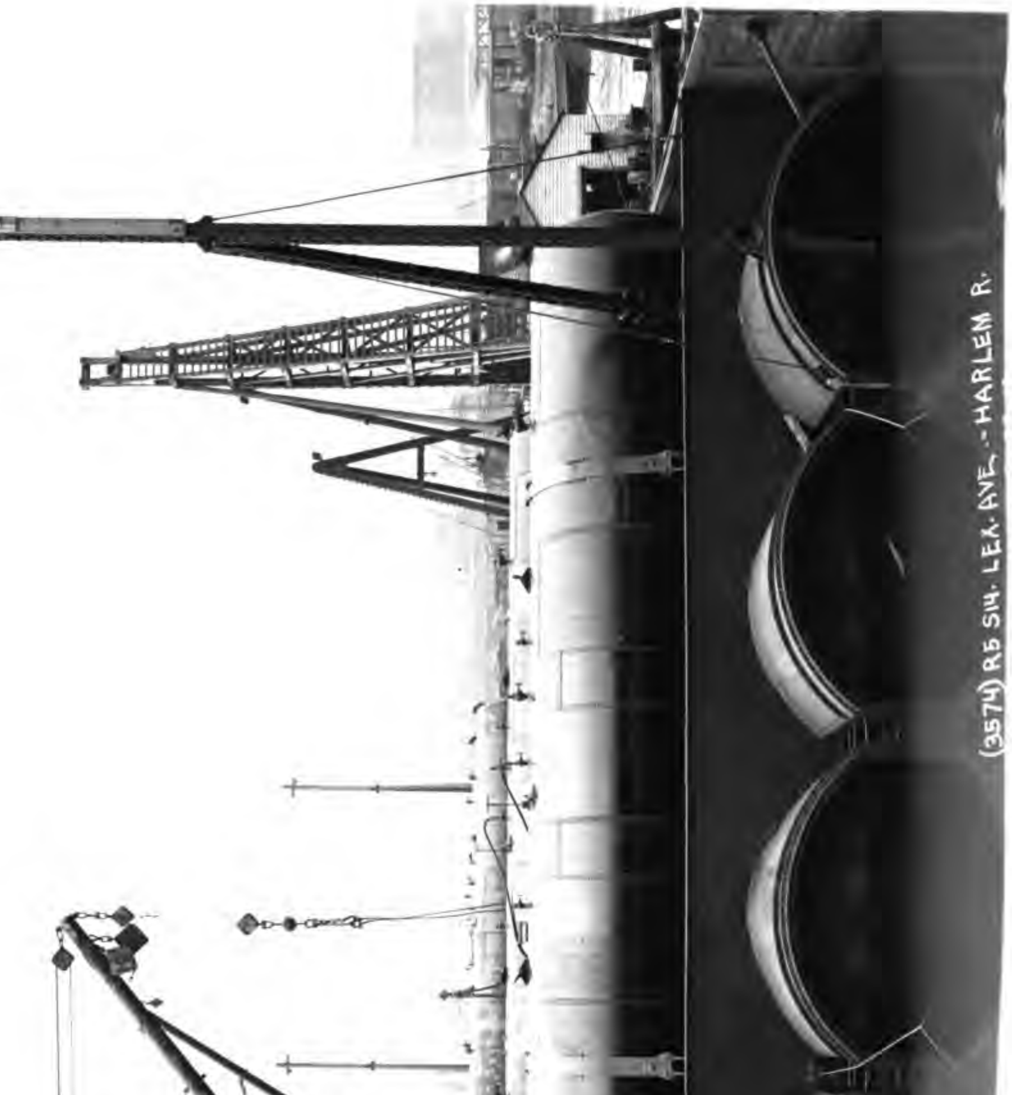

Figure 13

by wooden bracing and having a timber about 40 feet long fast

Section"B" placed upon flat boats and being towed

out of the "slip".

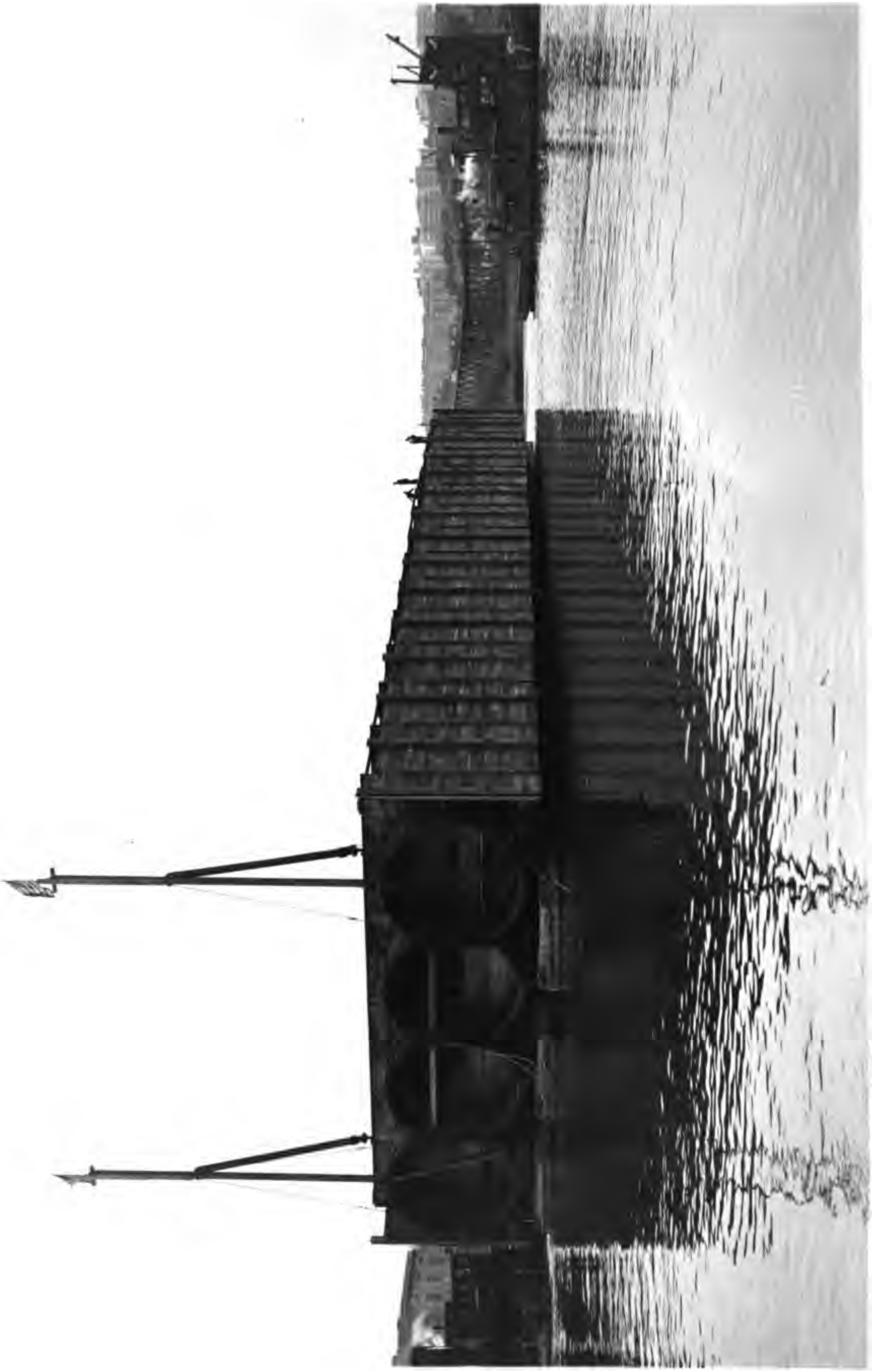

Figure 11

by wooden bracing and having a timber about 40 feet long faste

Section "B" after being towed out of the "slip" in process of being turned partially around before launching.

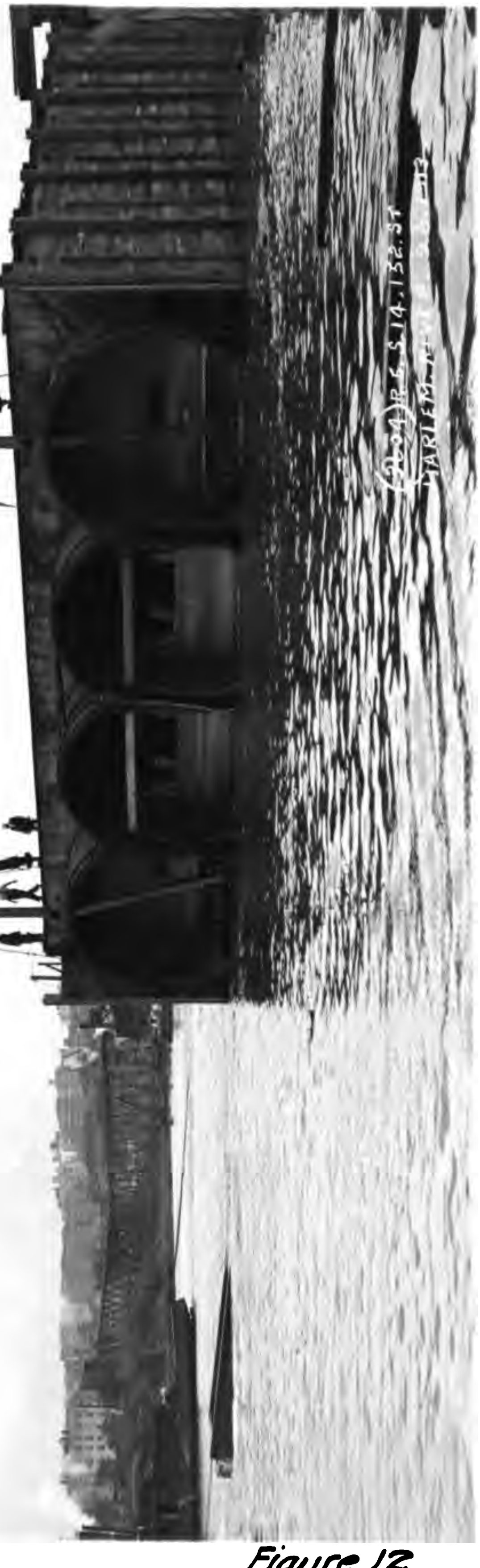

Figure 12

by wooden bracing and having a timber about 40 feet long faste

Section "B" after being launched, showing flat boat being pulled from beneath .

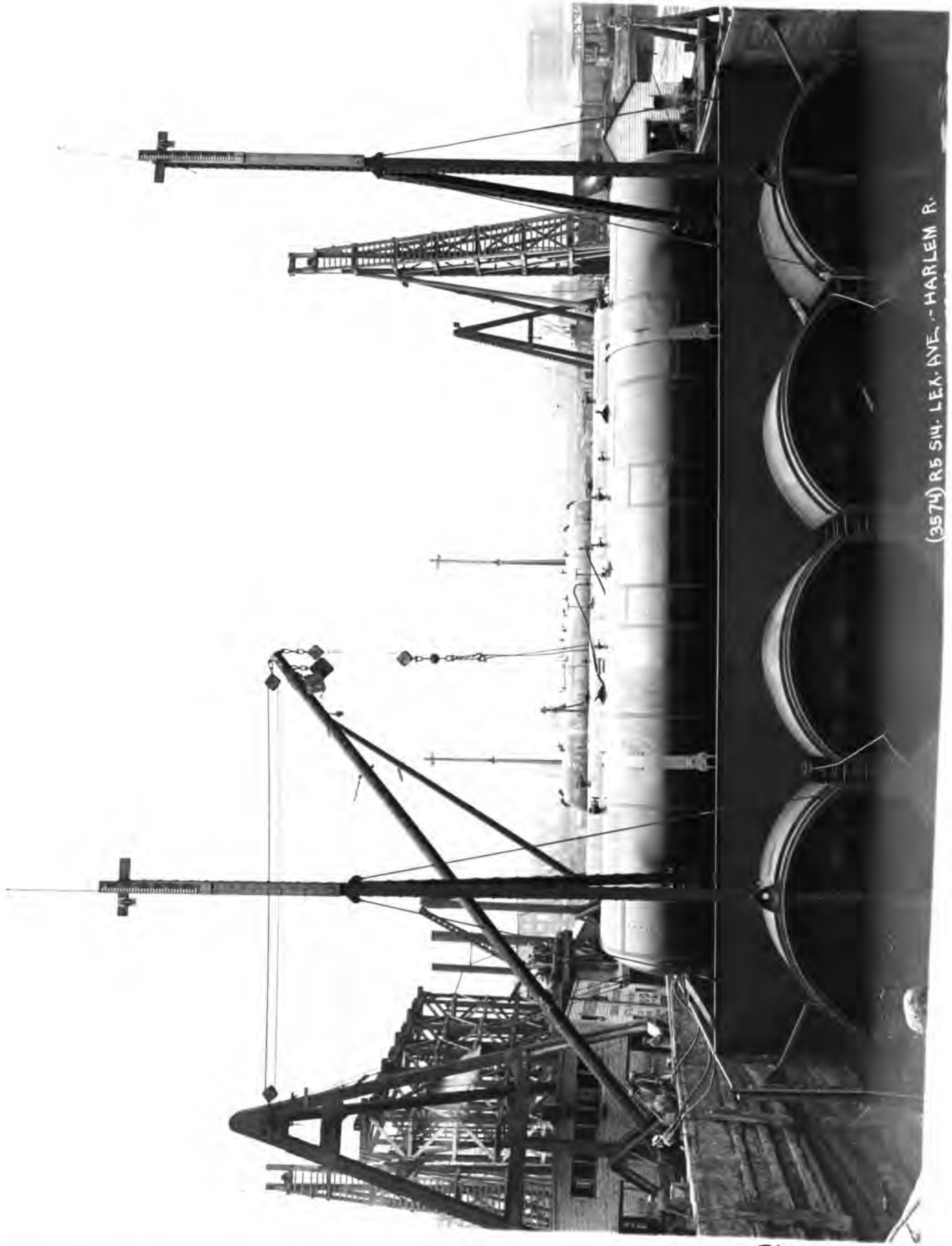

Figure 13

by wooden bracing and having a timber about 40 feet long faste

Section "A" (south end) showing details of buoyancy chambers and general details of plant arrangements and Tube details.

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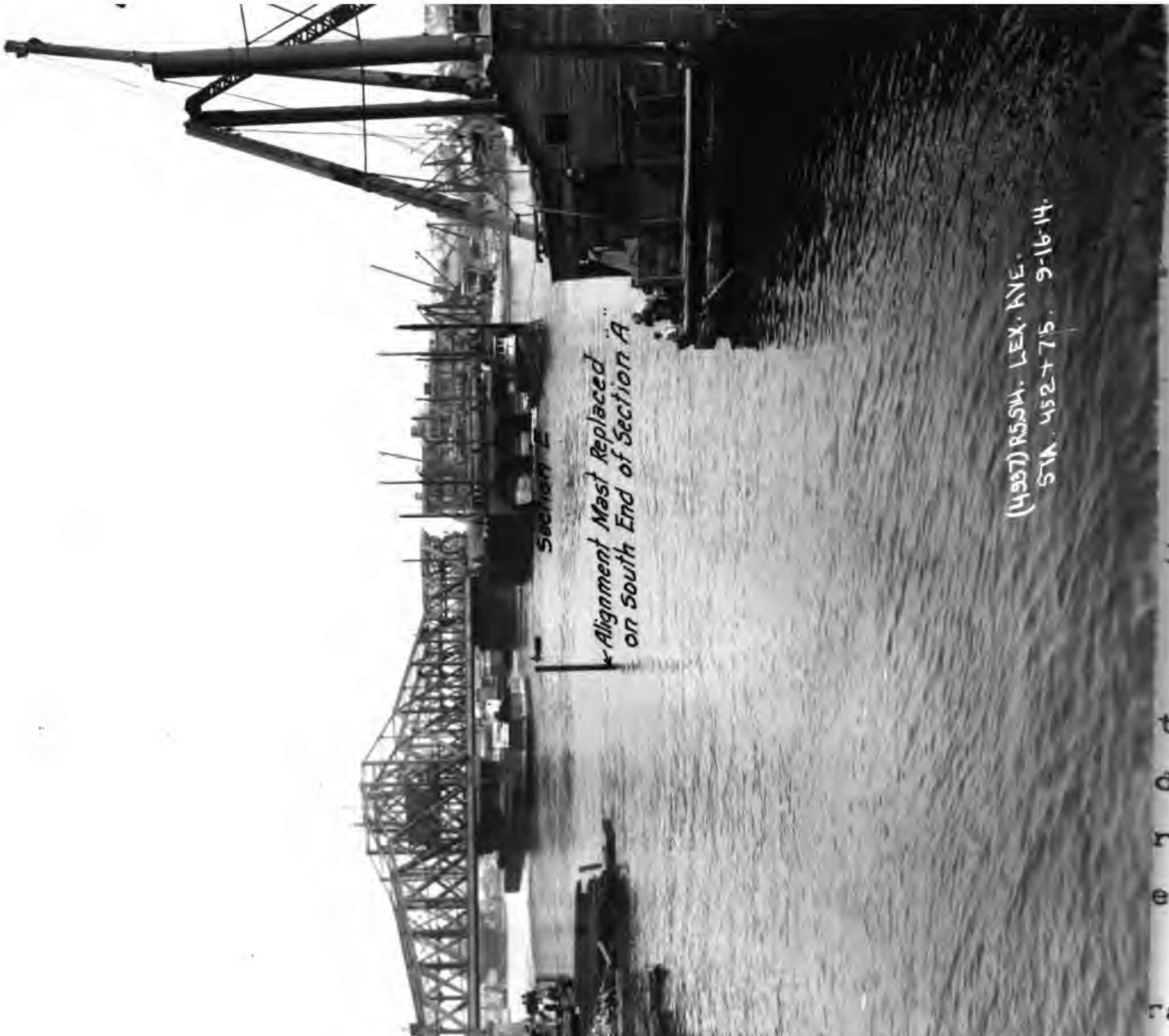

Alignment Mast Replaced on South End of Section A

(4937) R.5.Sh. LEX. AVE. STA. 452+75. 9-16-14.

Figure 14

two fabricated steel columns 60 feet long,held about 10 fe

by wooden bracing and having a timber about 40 feet long f

Route 5---Section 14

Harlem River Tubes

Construction Photograph

No. 4937

General view showing Section "E" and plant for sinking of section, looking north. Taken September 16, 1914.

interesting stages of the launching.

After the launching, four steel cylinders or buoyancy chambers were placed in position by means of a large floating derrick, two of them being placed near each end. These chambers rested upon shallow wooden cradles placed on the crown plates of the tubes and were attached to the diaphragms by two steel bands 12 inches wide and 5/8 of an inch in thickness, passing over the top of the cylinder as shown in Figure 13. Each strap terminates in two 1¾ inch square rods with an eye at the end to receive a 3-inch bolt. Upon these bands and the strength of their connections a great deal depends, for the whole weight of the structure is carried by them during the latter part of the sinking operations. With the Section equipped as above described, it was ready to be towed down the River and lowered into position. In order to keep the structure under absolute control, two tugs were used in front and one in the rear to keep it in its course and the tow to the site made against the tide in order that stops could be made at the several draw bridges while they were being opened. Figure 14 shows a Section in tow although all of the tugs are not visible.

PREPARATIONS FOR SINKING.

That the dredging had been completed for the Section to be lowered was usually determined by soundings taken over its limits on definite range lines by means of a lead line. However in the Sections where rock was encountered, it was not thought feasible to rely upon this determination for a projecting piece of rock might readily escape detection and damage the steel structure materially. Accordingly a "sweep" was rigged up consisting of two fabricated steel columns 60 feet long, held about 10 feet apart by wooden bracing and having a timber about 40 feet long fastened

Section "B" after being launched, showing flat boat being pulled from beneath .

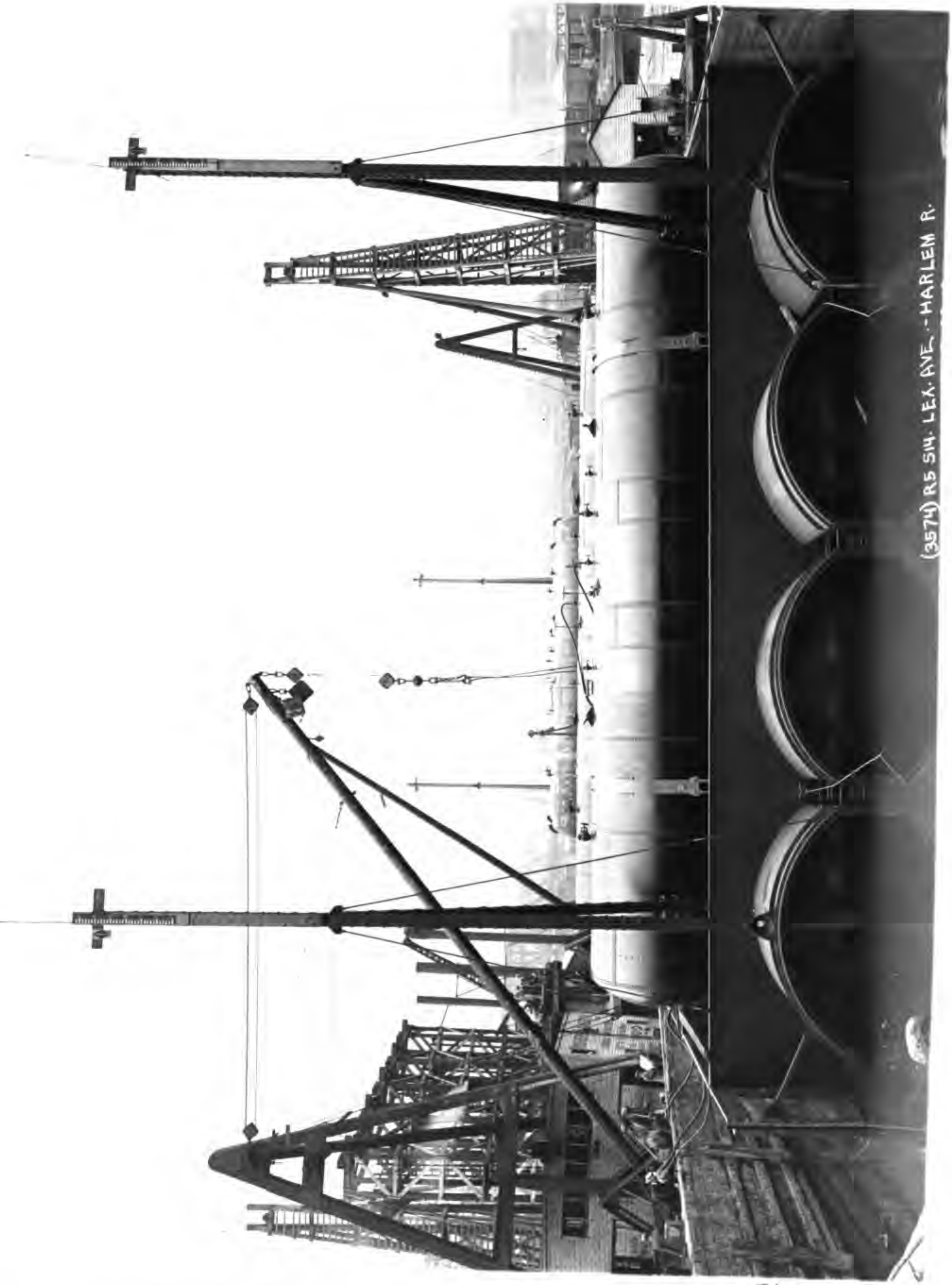

Figure 13

by wooden bracing and having a timber about 40 feet long faste

Section "A" (south end) showing details of buoyancy chambers and general details of plant arrangements and Tube details.

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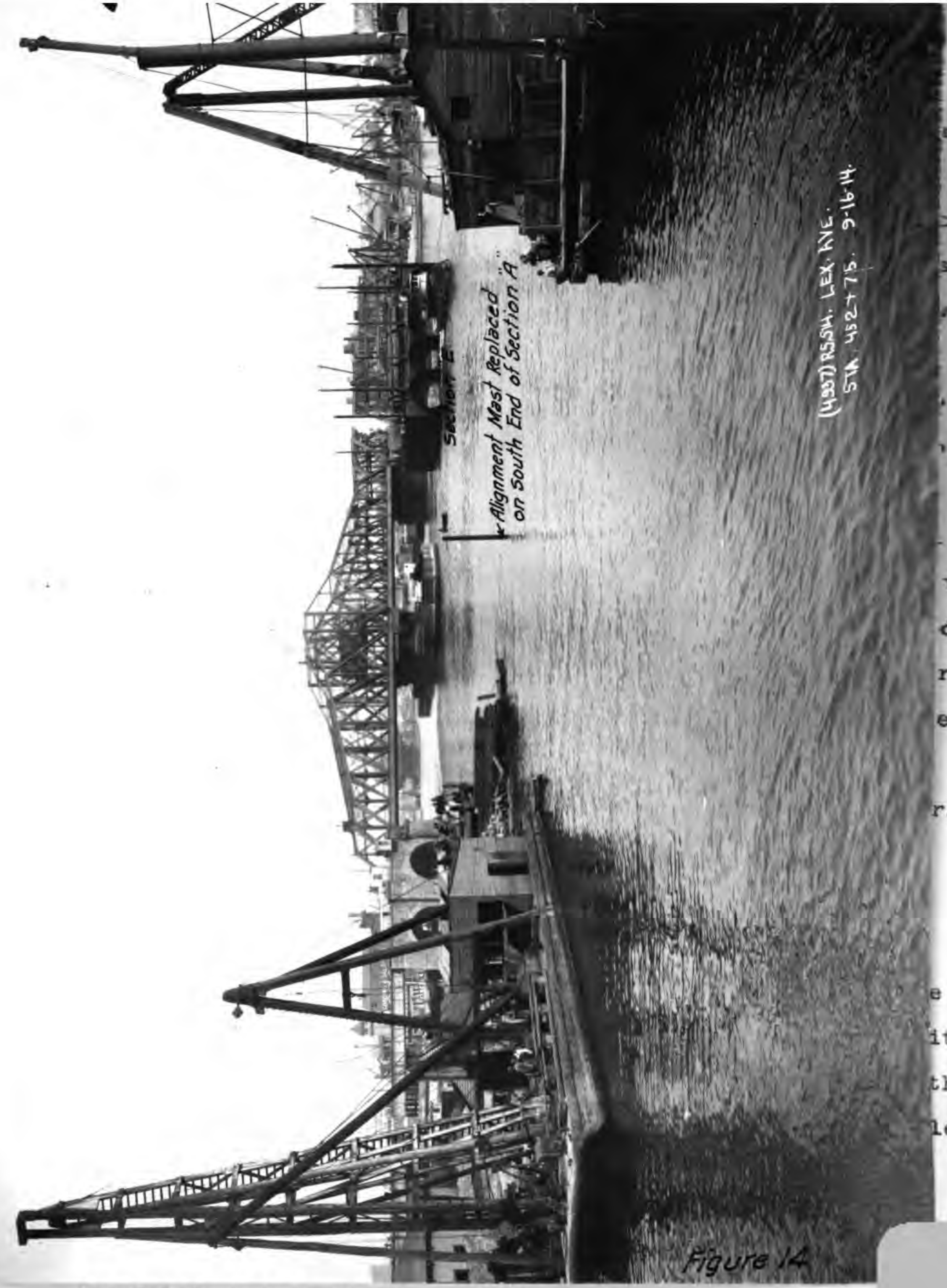
Section E
Alignment Mast Replaced on South End of Section 'A'
(4937) R.S.SM. LEX. AVE. STA. 452+75. 9-16-14.

Figure 14

two fabricated steel columns 60 feet long, held about 10 fee
by wooden bracing and having a timber about 40 feet long fa

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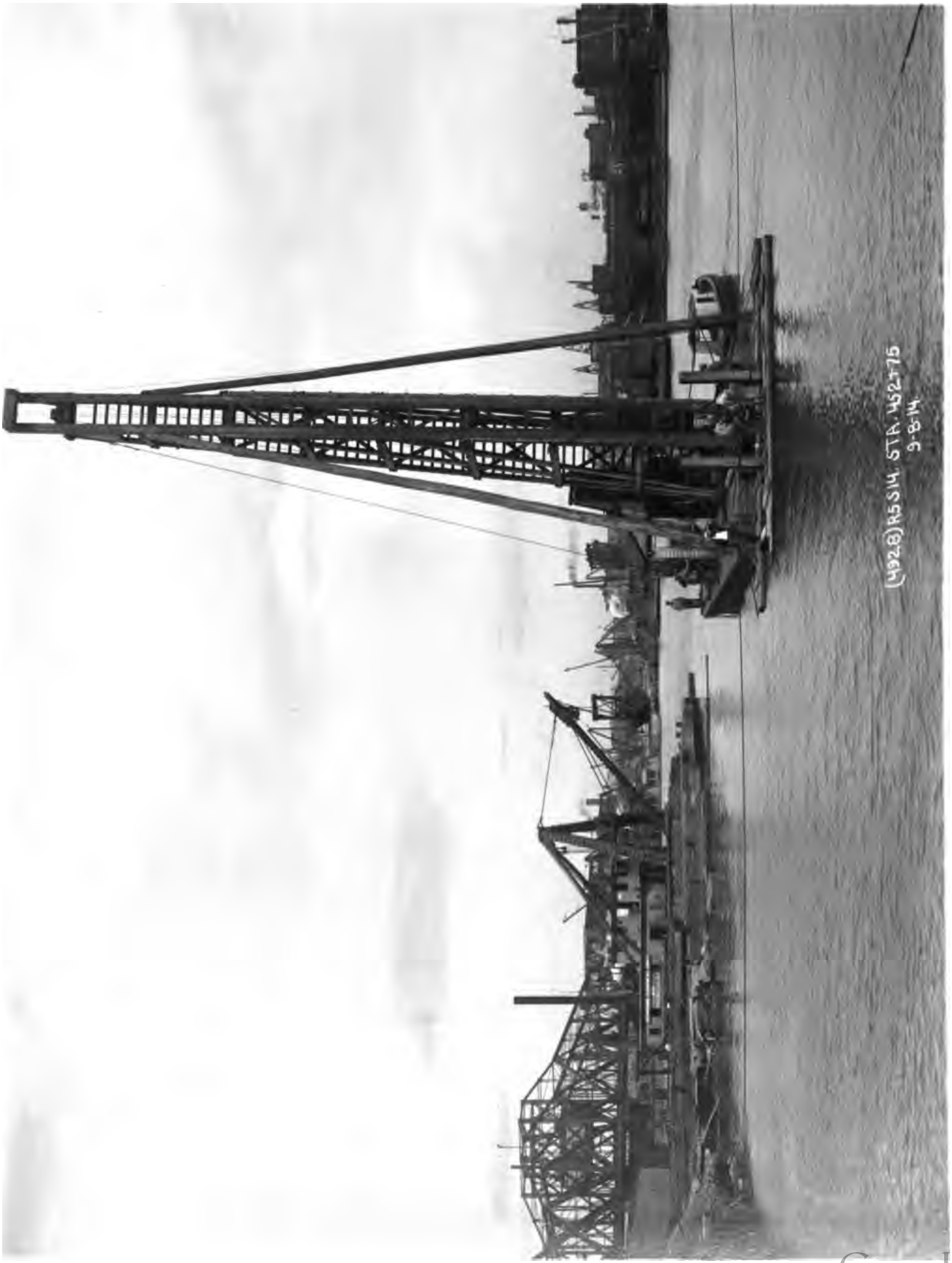


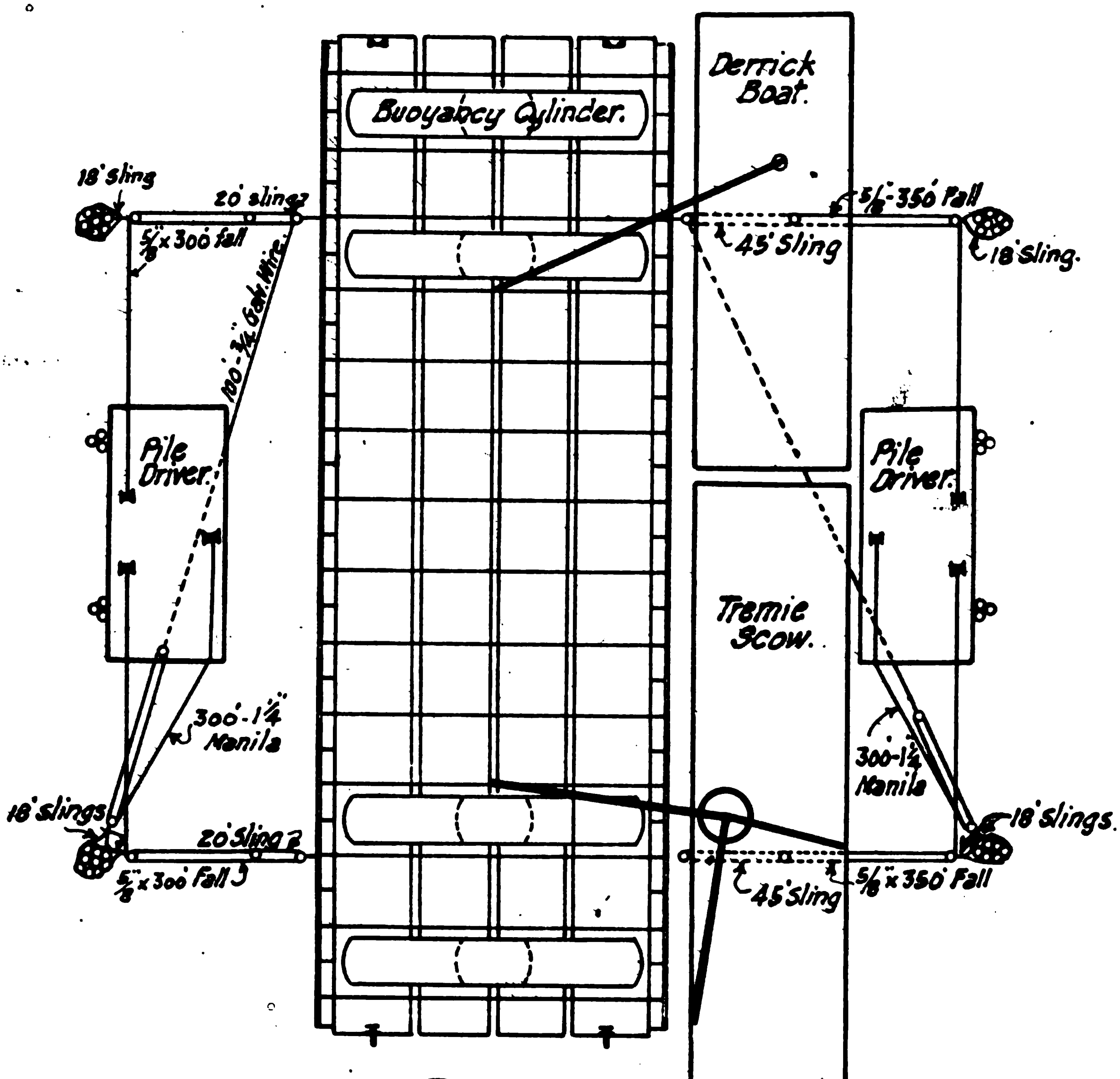
Figure 15

Google

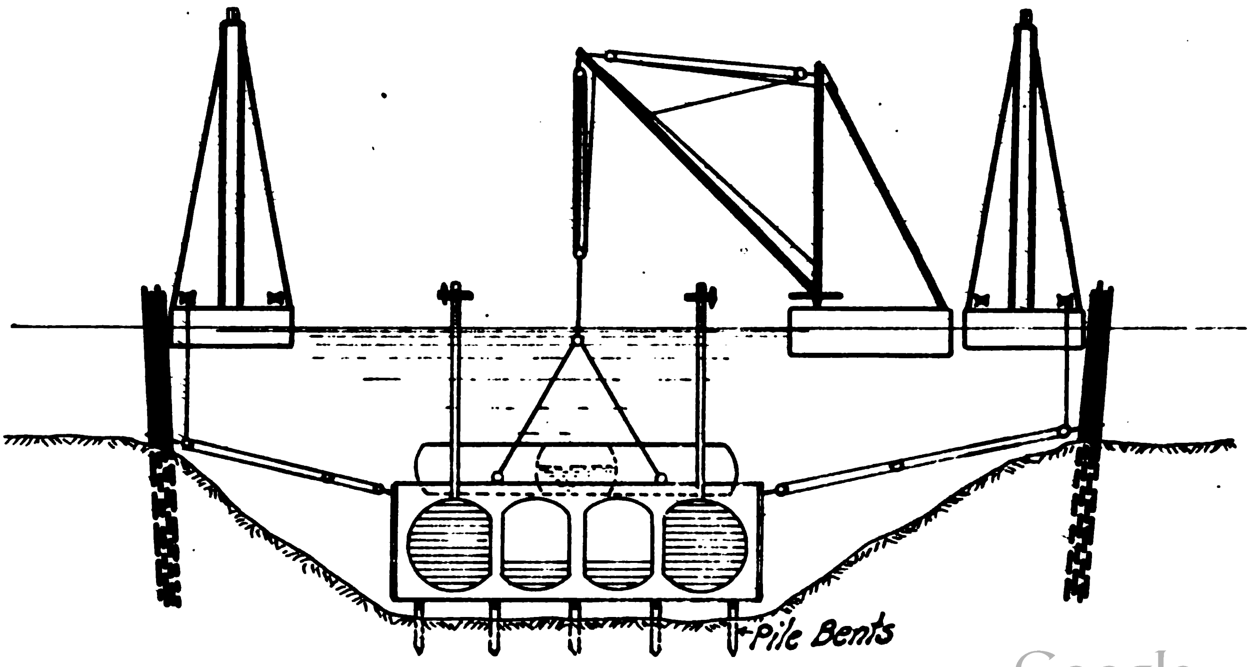
"Sweep" in the middle of Section "E" working alon the west neat line. Diver is preparing to go down to investigate an obstruction. Clam shell dredge shown in background was used to excavate some of the rock in this Section.

across the bottom ends at right angles to the columns. When the columns were suspended from the fall line of a pile driver as in Figure15, this timber remained in a horizontal position and by lowering it to the subgrade elevation and keeping the steel columns on line with a transit, any encroachments were readily and accurately located as the pile driver moved slowly over the trench. A diver was sent down whenever an obstruction was found, to report on the nature and extent of it and to remove it if possible.

Having satisfactorily determined that the trench had been excavated to grade, the next step was to provide a definite support for the structure at the proper elevation until the exterior concrete could be placed. This temporary support was provided by pile bents driven generally under the end diaphragm, using from 3 to 6 bents in each case. These bents consisted of two 12" x 12" posts properly pointed and capped by two 12" channels 10 feet long (one on each side of the posts), the whole being braced rigidly and bolted so that when driven into the firm foundation materials of the trench, they provided ample support for the structure. In the first Section, it was necessary to drive these bents under the last diaphragm at each end, but in the remaining Sections they were placed under the free end only, the strength of the junction connections being depended upon to hold the other end in position. In the driving of these bents, they were made fast to the "sweep" frame previously referred to, with a column over each post or pile and two pile drivers lashed togetherwith a steam hammer acting simultaneously on each column, drove the bents without difficulty and very close to the designed grade of the diaphragms. In general the foundation materials were so compacted that a penetration of from 5 to 8 feet for these piles was all that was necessary to give the desired support.



PLAN.



SECTION

Figure 16

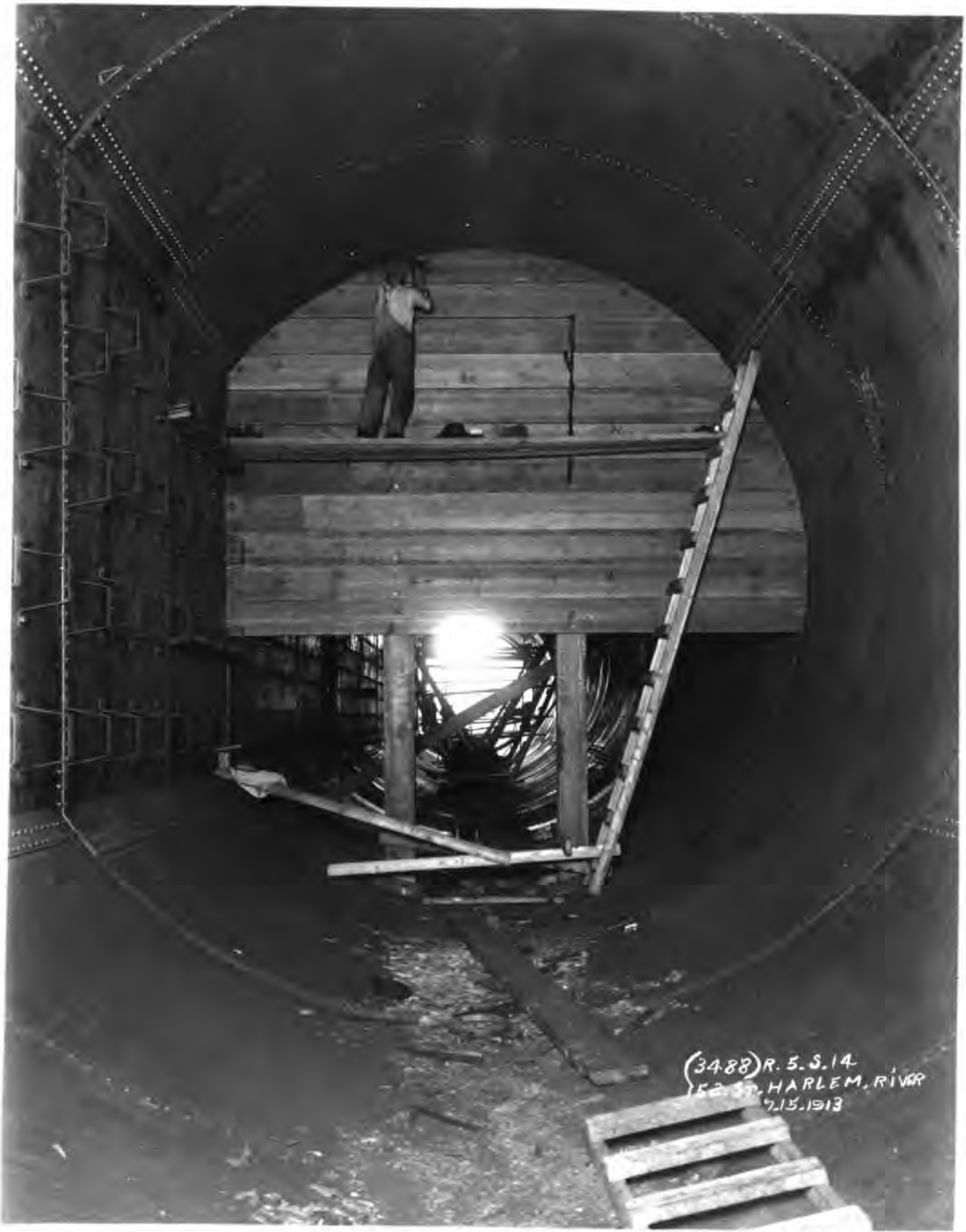


Figure 17

the structure; one at each end about 50 feet long with a 2-inc

View of timber semi-bulkhead in outside Tube of Section "A". Workman is "ship caulking" the bulkhead using oakum.

A structure of this size presents considerable surface for the action of tides, which at this point attain a maximum velocity of 1.7 feet per second, making it necessary to provide substantial anchorages to keep the plant and tubes in position and under control. Clusters of piles driven about as indicated in Figure 16 & 22 and also visible in some of the photographs of the sinking operations, were used where substantial anchorages on shore were not available. Wire rope cables operated from the "niggerheads" of two pile drivers rigged as shown in Figure 16, readily controlled the locating and shifting of the Section.

SINKING OF THE TUBES.

This operation depends for its success upon the gradual filling of the tubes with water and suspending them by buoyancy cylinders until this condition is obtained, then under a positive and accessible control gradually overcom~~e~~ing this excess buoyancy of the cylinders by an amount which can be safely handled by an ordinary derrick boat and gradually lowering the structure into position. The control for the admission of water to the tubes was for obvious reasons confined to the outside tubes, the center tubes being allowed to fill with water as the Section became submerged.

The first thing to be done was to open simultaneously the 12" gate valves fitted into the bulkheads of the outside tubes near the bottom (Figure 9), allowing the water to flow into the structure. When the water had filled the tubes to about the height of the axis, it met two bulkheads placed in the upper half of the outer tubes about 50 feet from the end bulkheads. This bulkhead is shown in Figure 17. At this stage there were in each of the outer tubes essentially three air chambers in the upper part of the structure, one at each end about 50 feet long with a 2-inch

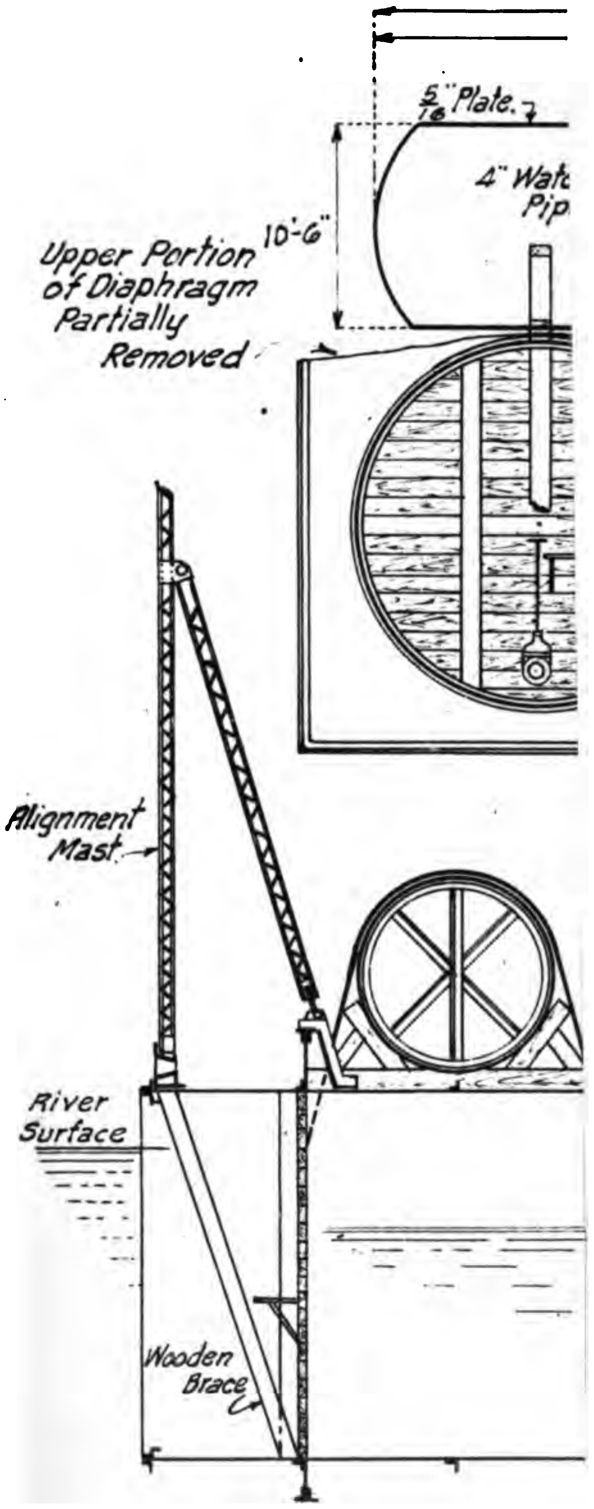


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Figure 18

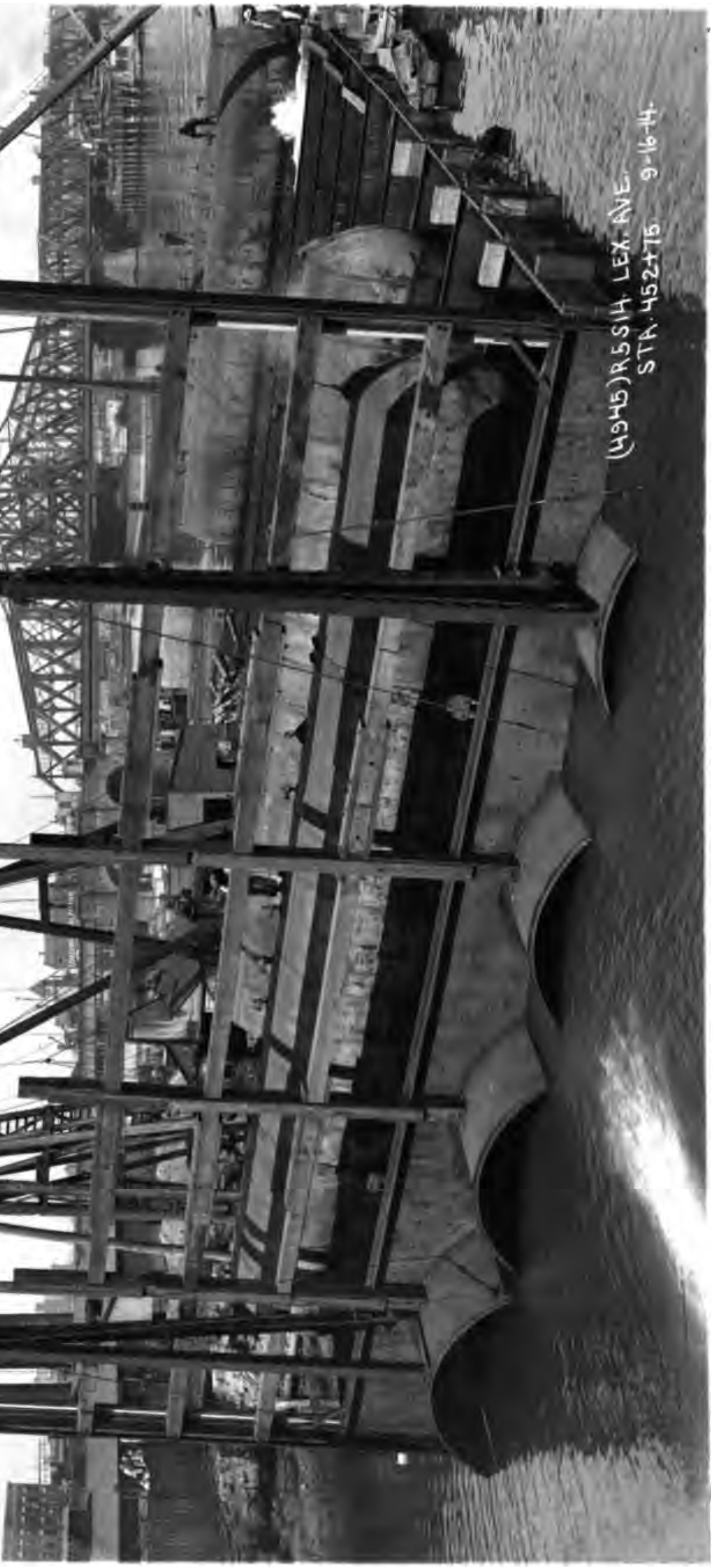


Figure 19

Section "E" in position with Tubes partially filled with water and listing to the east due to the larger amount of water in the east Tube. The frame erected on the last diaphragm, is to furnish a support for the wooden bulkhead which was placed later to protect the excavation work on the South Approach. A section of steel sheeting is attached to the east and west edges of the last diaphragm in order to form a tight joint at this point.

air exhaust opening at the top, and a chamber about 110 feet long in the central portion of the tube with a 3-inch air exhaust opening at each end of the chamber. This condition is indicated in the longitudinal section shown in Figure 18. The purpose of these semi-bulkheads and the air chambers formed by them and the water in the tubes, was to prevent any sudden diving which might occur if one of the valves should become clogged, or if for any reason the Section should become unbalanced and cause the water to rush to one end of the tube. These bulkheads alone would only have served to retard such a tendency and without some other control they would have been of comparatively little use. This control was obtained by fitting a 15-foot length of pipe into each of the 2-inch openings and leaning these pipes against the buoyancy cylinders so that the valves on these pipes were readily accessible and could be operated by workmen standing upon these cylinders. In case one end of the Section filled with water faster than the other, the valves at that end were closed, the effect being to increase the air pressure in the small end compartment and thereby retard the admission of water to that end until equilibrium was established. The operation of this control was very satisfactory and readily corrected such differences in level as that indicated in Figure 19.

As the water entered the tubes displacing the air, they gradually lost their buoyancy and if there had been no other provision, the tubes when nearly full of water would have instantly gone to the bottom. On account of the circular form of the tubes after the water rises well above the axis, the ratio of the effective buoyancy to the volume of water decreases so rapidly that before the tubes are filled with water they are submerged. This

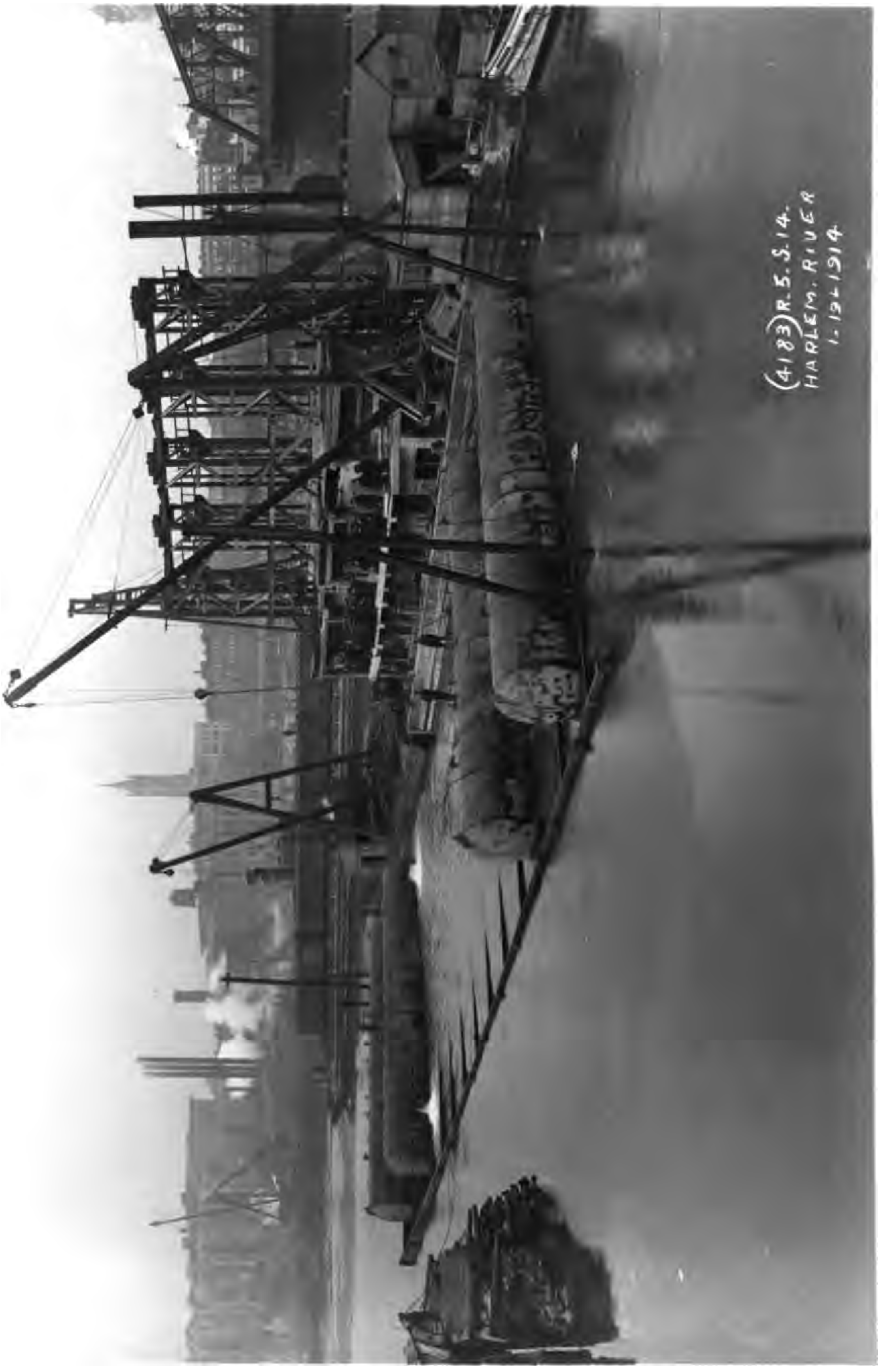


Figure 20

in the bottom, enough water was admitted to the center compartm

Section "C" in position and almost filled with water.

Tremie scow in the back ground.

can be noted by refering to Figure 20 which plainly shows the air still exhausting from the 3-inch openings although the tubes are under water. The position of the buoyancy chambers causes them to begin to be effective as soon as the water submerges the tubes, and the transition of the suspending force from the air chambers in the upper portion of the tubes to these cylinders was so gradual that the change was scarcely noticeable.

The buoyancy cylinders were divided into three compartments, a small center compartment about 15 feet long and two end compartments about 26½ feet long. Each of the three compartments was fitted with a 2-inch air valve and with a water valve having a pipe extending within 1½" of the bottom of the cylinder, the valves all being operated from the outside top of the chamber. The chief function of these valves was to provide a means of unwatering these chambers, which was done by applying air pressure at the air valve and forcing the water out through the water pipe, in order to recover them after they had performed their work on one Section. These compartments and the valves are indicated in Figure 18 and may also be determined in the photographs which show these cylinders in sufficient detail. The center compartment had in addition to the valves noted, a 3-inch valve located on the inside at the bottom and controlled by a long stem extending through a stuffing box at the top, for the admission of water. When the tubes were completely filled, which was indicated when the air ceased to exhaust from the 2 and 3" openings at the top of the outer tubes, the structure depended for its suspension entirely upon these chambers which were filled with air and together had a buoyancy effect in excess of the weight of the submerged structure of about 76 tons or 19 tons for each chamber. By means of the water valve in the bottom, enough water was admitted to the center compartment

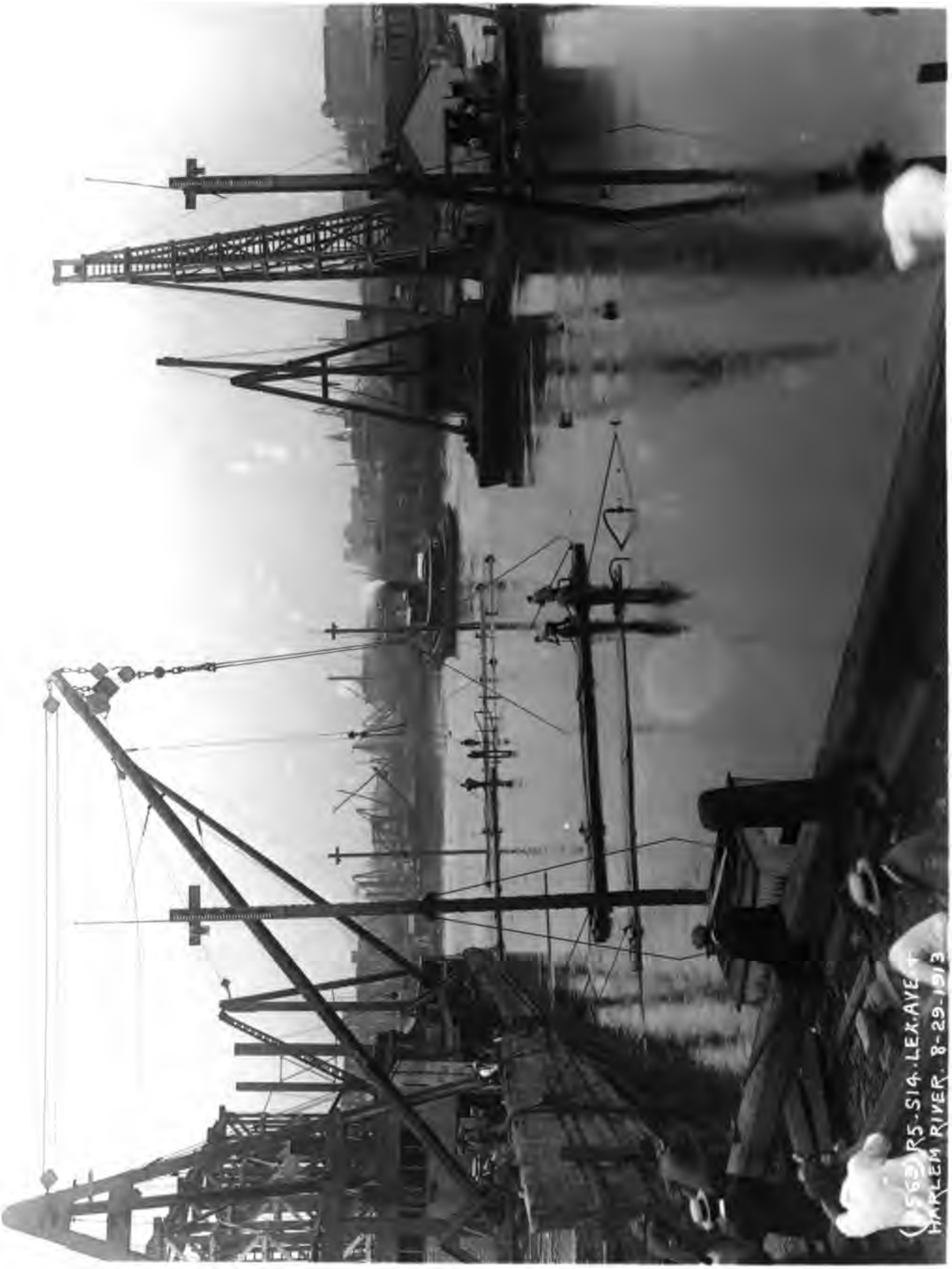


Figure 21

These masts were centered over and attached to the junction c

Section "A" with excess buoyancy overcome in the south end and nearly so in the north end, and about ready to be lowered.

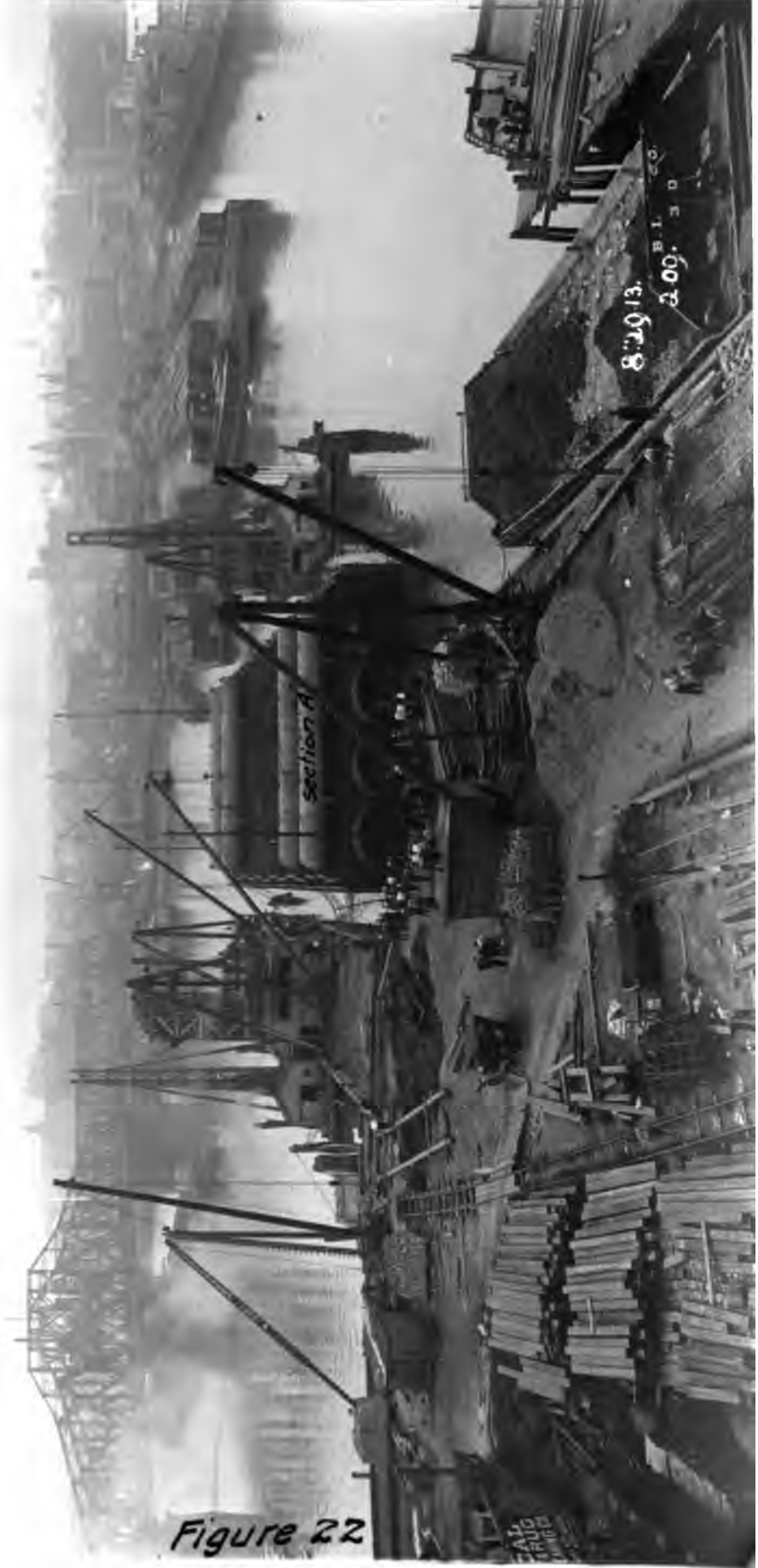


Figure 22

when the section was in place.

These masts were centered over and attached to the junction cast-

Section A in position , with lowering plant assembled.

and under perfect control, to overcome this excess buoyancy. When this was accomplished the middle compartment was only half full of water leaving a comfortable margin of safety in either direction in case the Section should vary from the computed weight.

In order to produce a positive downward resultant for the resistance of tidal action and for stability when finally located, some water in addition to that necessary to overcome the buoyancy was admitted to the center compartments. This total excess load was readily handled by two derrick boats and probably did not exceed 20 tons in any case. In event that too much water should have been admitted, it could have been easily removed through the water pipes by applying air pressure. Also the tubes could have been raised again to the surface if necessary for any reason by the same device. The derricks for lowering the Section were attached to it by means of cables placed about 50 feet from each end as shown in Figure 21, and when everything was in readiness the structure was carefully lowered upon the temporary pile bents and the tubes brought into alignment by means of cables previously attached to the ends and sides. The whole operation of lowering a Section from the time that the valves in the bulkheads were opened until the structure was in final position, has required almost exactly three hours for each of them.

METHOD OF JOINING THE SECTIONS.

In order to join any Section to the one previously placed, masts were erected at the ends and over the center line of the outer tubes as shown in Figures 9 and 12, having a length sufficient to project above the water when the Section was in place. These masts were centered over and attached to the junction cast-

ings to be described later and were carefully plumbed so that the center of the masts were in a vertical plane with the center of these castings and the axes of the tubes. For the convenience of making alignment observations, one-foot offset lines were established and targets placed on a projecting arm so that the position of the masts on both ends could be determined from the same point of observation. A duplication of the usual type of self-reading level rod, was mounted on each mast and set so that when the tube was at its designed elevation, the reading on the rod was the height of the instrument. This formed a very convenient and accurate method of determining immediately how much it was necessary to raise or lower the structure at either end, and although it was never necessary to do so, the instrument work for setting a Section in position could have readily been done by two men.

A simple and satisfactory device was used for guiding the tubes into position at their abutting ends and holding them together. At one end of the outer tubes of Sections B, C, D and E a casting was mounted on the crown shell plate and held a 5-inch pin which was tapered at its point and projected about 2 feet beyond the end of the Section. In a corresponding position on the adjoining Section, a casting with a hole tapered from 17" down to the size of the pin was placed. An alignment mast replaced upon the Section in position served as a satisfactory guide for bringing the Sections together so that the pin entered the tapered hole and gradually forced the tubes into proper alignment and by means of steel wedges through the pin, held them there. A detail of this connection is shown in Figure 18. In view of the stresses which would come upon these pins and their connections if there was any considerable movement of the free end due to tides or

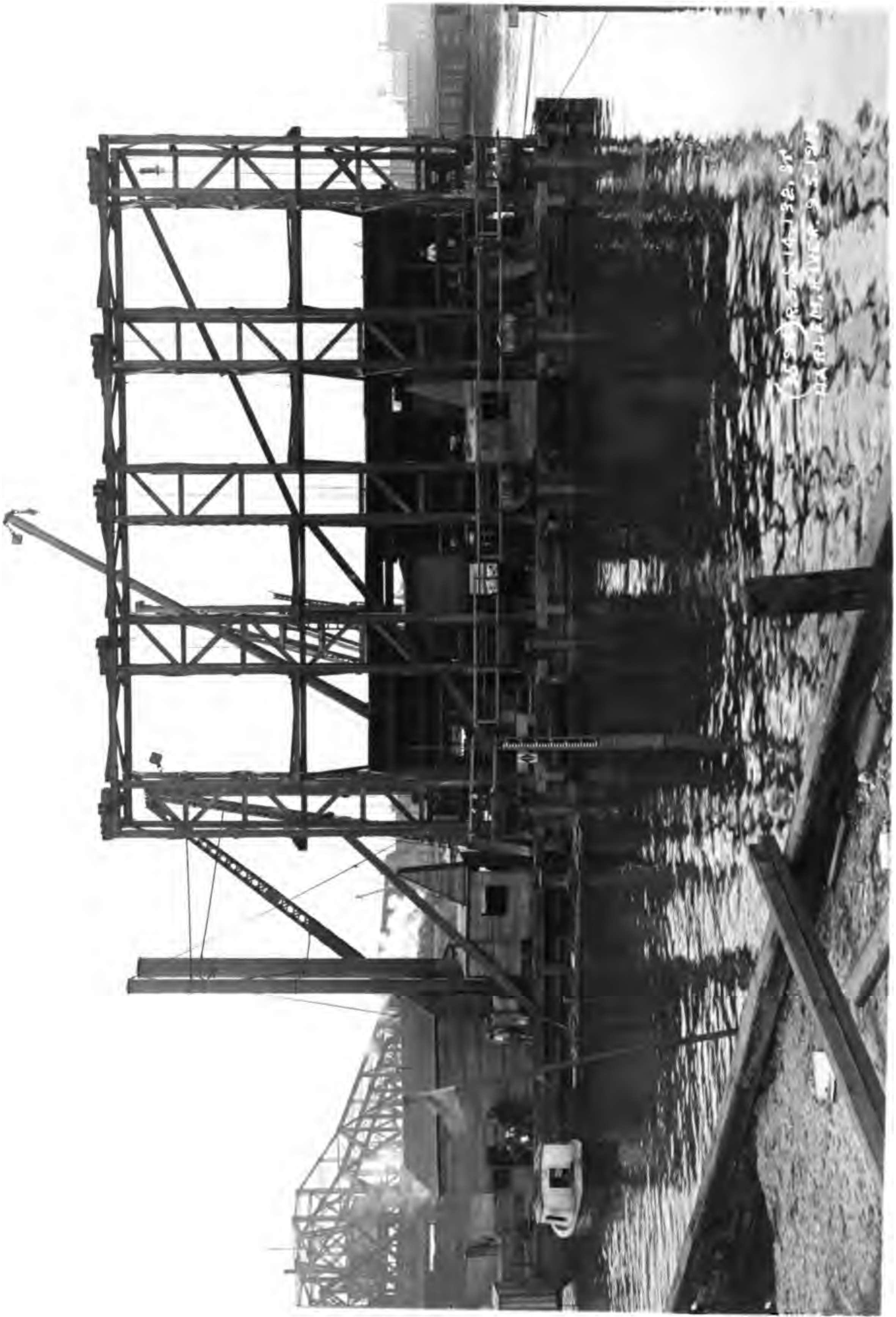


Figure 23

[illegible]

water storage tanks were built in the bottom portion of the bar

Tremie scow depositing exterior concrete in the foundation of Section "A". The mast of the west tube is visible in the left-center fore ground.

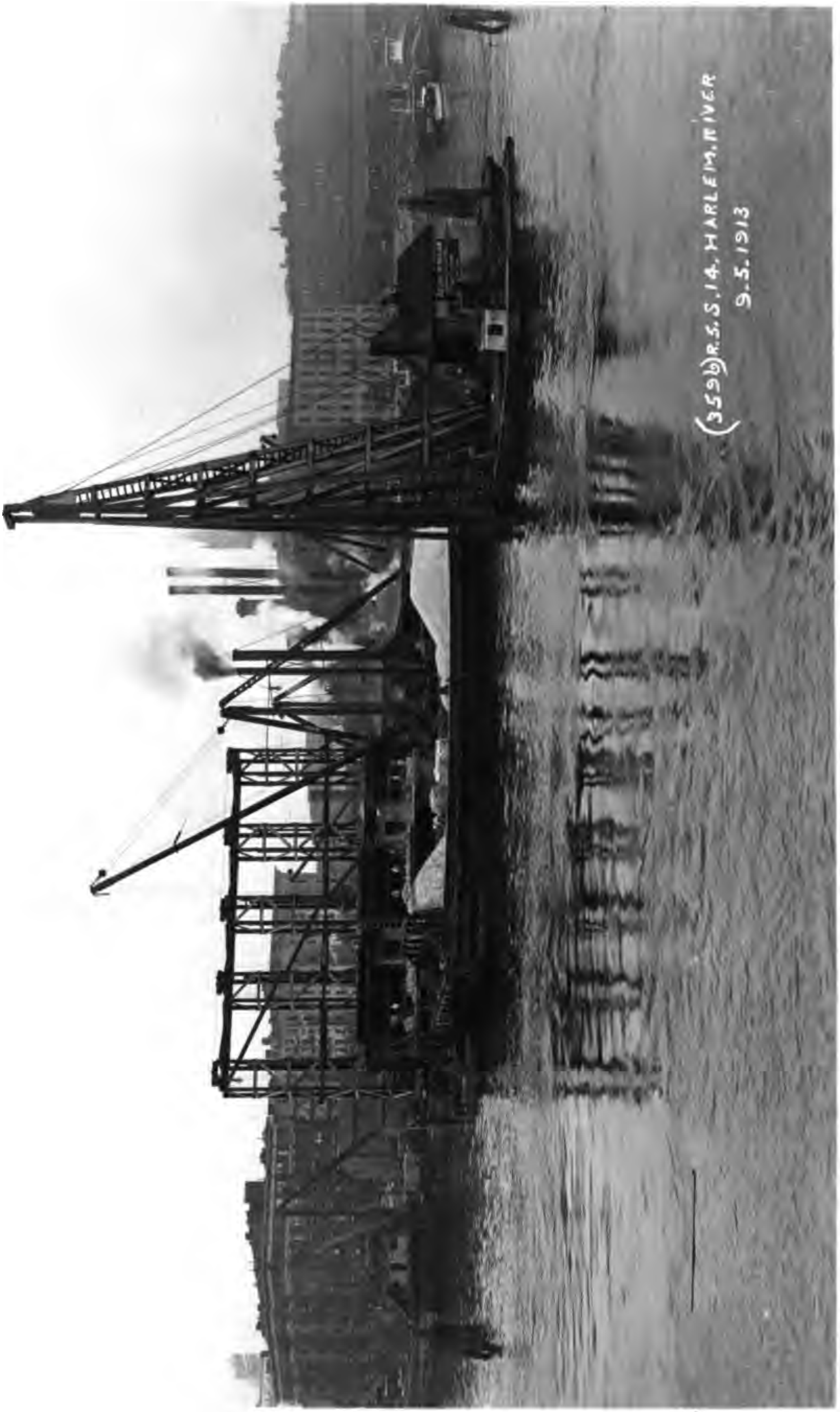

(3596) R.S.S.14. HARLEM.RIVER
9.5.1913

Figure 24

[illegible]

water storage tanks were built in the bottom portion of the b

Tremie scow ,showing view of

loading derrick and material barges alongside.

other causes, the projecting legs of the reinforcing angles which are riveted to the shell plates for the entire periphery of the four tubes, were connected by 7/8-inch bolts 10 inches long and spaced about 18 inches on centers. (Figures 9 and 18.) These bolts were placed by divers as soon as possible after the structure was in final position.

EXTERIOR CONCRETING.

With the Section in place, the encaseing of it was started generally the next day. Figures 23 and 24 show front and rear views of the special plant constructed for this purpose. Briefly it consisted of three complete mixing plants serving five tremie pipes mounted on wooden towers, with two large boilers to furnish power for the operation of the various engines and hoists including the loading derrick. The wooden towers (50 feet in height) were spaced about 17 feet on centers and served the double purpose of a guide for the tremie charging bucket and for the support of the tremie hopper to which the tremie pipe was attached. The charging buckets were filled by three rotary batch mixers, one mixer serving each pair of extreme pipes and one the center pipe. Aggregate bins holding about 20 cubic yards each of sand and gravel, were placed directly above the mixers which they served and were supplied by means of the derrick from barges tied along side. Although there was a cement storage room large enough to hold about 250 barrels provided, the cement was usually obtained directly from the cement barge in the same manner as the aggregate. An old freight car lighter 37 feet wide was cut down so that it was 140 feet long and served as a float upon which this plant was assembled. Fresh water was required in the mixing of concrete so that water storage tanks were built in the bottom portion of the barge.

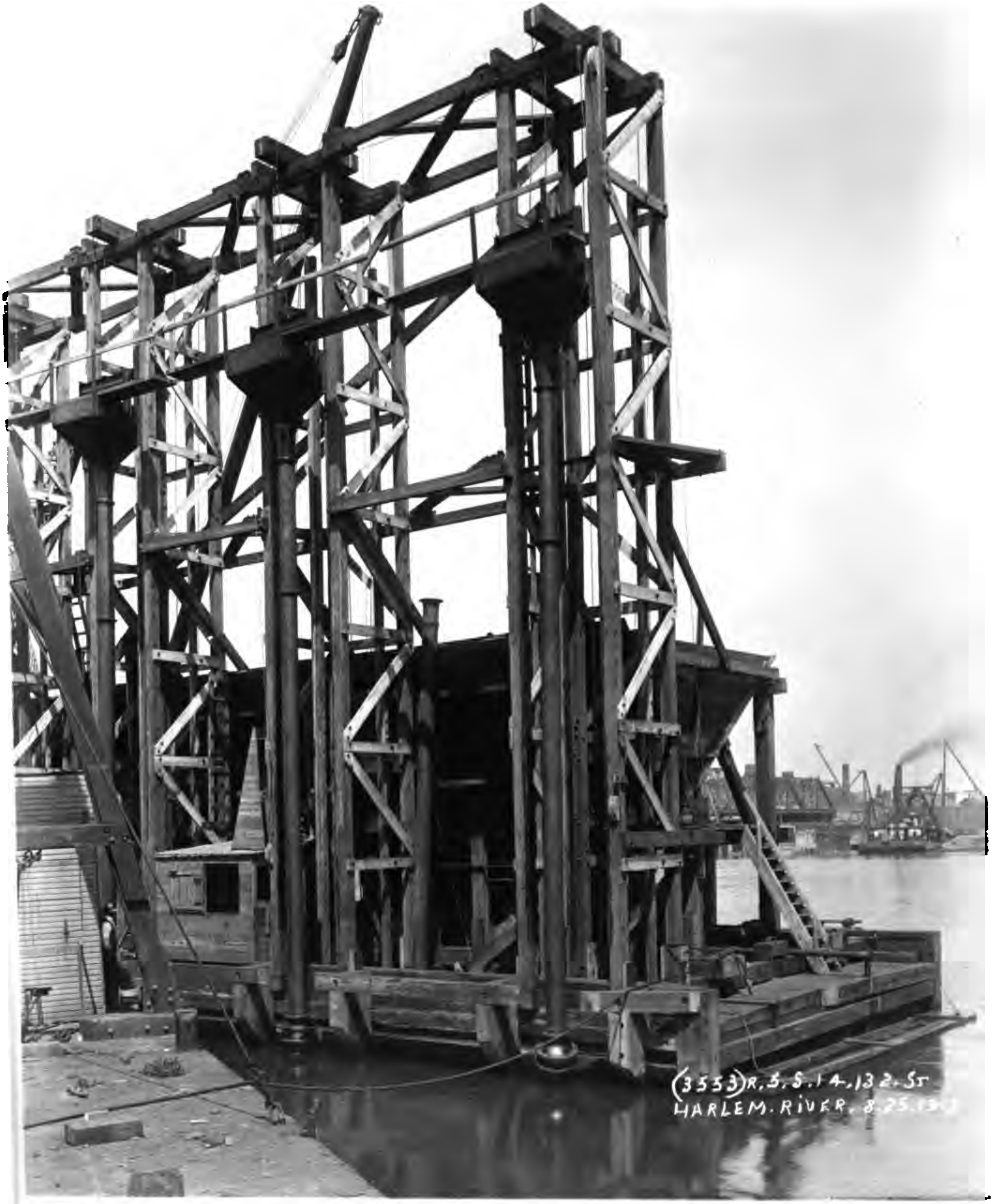


Figure 25

operators became so expert in controlling the discharge that

Detail view of tremie pipe, hopper platform and general details.

The tremies were made of 12-inch diameter spiral riveted pipe 63 feet long, suspended from a hopper which could be raised or lowered at the will of the tremie operator from the hopper platform, by means of an endless rope working over a series of pulleys which controlled the throttle of a single drum hoisting engine. A ball and socket or swivel joint was placed about 30 feet below the hopper, in order to accomodate any shifting of the scow or listing due to the operation of the loading derrick or swells from passing boats. This provision gave the pipe ample flexibility and without doubt saved many anneying delays from broken pipes and lost batches of concrete. Figure 25 shows this joint in detail.

In their operation the tremies were first guided into position by the diver, a pipe being placed on each side of the four tubes, and one dry batch of concrete was dumped into each of the pipes acting as a plunger to force the water out and seal the bottom, immediately after which they were filled with wet concrete two batches being sufficient to fill the pipe. As fast as the concrete oozed or boiled out at the bottom of the tremies it was supplied at the top. The essential requirement for the satisfactory operation of the tremie method of depositing, is to maintain a continuous or nearly continuous flow of concrete directly to its final position with as little movement as possible and gradually replace the water with concrete but without any mixing of them except at the contact surfaces. In meeting this requirement the tremie pipes were kept full of concrete maintaining a practically constant head upon the discharge end and, by keeping the end of the pipe submerged from 3 to 6 feet in the soft concrete, the flow was readily controlled by raising or lowering the pipe. The tremie operators became so expert in controlling the discharge that very

seldom was any trouble experienced with the sudden emptying of the pipe and the subsequent filling of the tremie with water.

At the beginning of concreting, the structure might be considered as a large box with sides and ends and a series of partitions at regular intervals but without a top or bottom. To form the bottom of the box and to provide a bearing for the diaphragms, concrete of the proportions 1:4:8 was deposited with the tremie and on the average was 3.5 feet in thickness representing the amount of the over-dredging. With the exception of Section E, practically all of this foundation concrete was deposited before any of the enveloping concrete was placed, except one or two pockets near the free end to assure a positive anchorage, after which the pockets were filled in any convenient order until the entire Section was encased. Two foundations or one pocket was usually considered a days work although two pockets were finished occasionally when an early start was possible. The contractor was naturally required to carry on his operations in any pocket continuously to its completion and in the case of Section E, where it was decided to complete each pocket including the foundation working continuously, it is now thought that this proceedure gave a more uniform contact between the concrete and the steelwork and prevented any accumulation of laitance or deposition of any kind upon the surface of the foundation concrete from becoming trapped and incorporated in the encasing concrete. An inspection was always made by a diver of the surface of the foundation concrete and any amount of foreign material removed before filling the pocket. It required on the average 22 working days of 8 hours to place the exterior concrete for each of the 220-foot Sections. The average output of the three mixers working 8 hours, was 360 yards with a

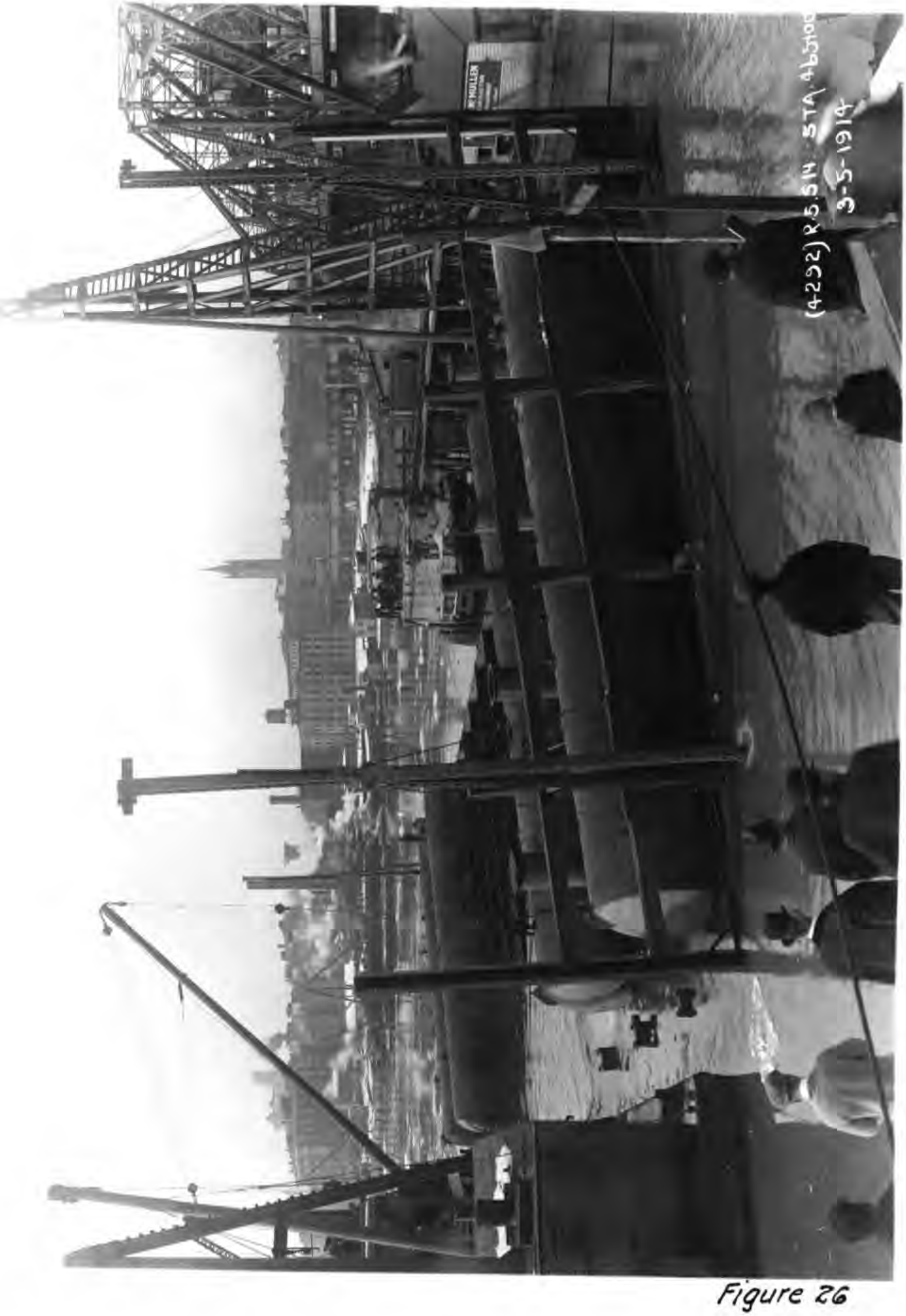


Figure 26

shafts were made in convenient lengths bolted together with le
ders up the sides and were arranged to be removed down to the

Section "D" partially submerged, showing access shafts and circular plate covering to make the end compartments air-tight. These plates were accessible after the tubes were filled with water and having served their purpose, were removed.

maximum of 700 yards and the plant was operated by a crew of 40 men including the diver and his helpers. The average cost of placing the exterior concrete was $1.00 per cubic yard.

The pockets covered by the buoyancy cylinders could not be encased until these cylinders were removed. Up to this time they were in the same condition as at the time of sinking, the center compartment being about half full of water and the end compartments empty. The tension upon the straps by which the cylinders were fastened to the structure, was relieved by filling all of the compartments with water after which the straps were released. Air pressure was then applied to the center compartment through the connections previously described and as the cylinder was gradually unwatered, enough buoyancy was produced to raise it to the surface. When the water had been exhausted from the center compartment, it was then removed from the ends after which the chamber was ready for use on the next Section.

UNWATERING OF THE TUBES.

It was predetermined that when Sections A, B, C and D had been encased in concrete, these Sections should be unwatered and lined with concrete before sinking Section E in order to protect the South Approach excavation which was much nearer the River than the North Approach work. Wooden bulkheads of sufficient strength to safely resist the full head of water, were placed in all four tubes in the south end of Section A (Figure 9) and the north end of Section D. The only means of access to the tubes was by means of cylindrical shafts 3 feet in diameter extending above high water and riveted to the top and over the center line of each tube near the north end of Section D as shown in Figure 26. These shafts were made in convenient lengths bolted together with ladders up the sides and were arranged to be removed down to the top

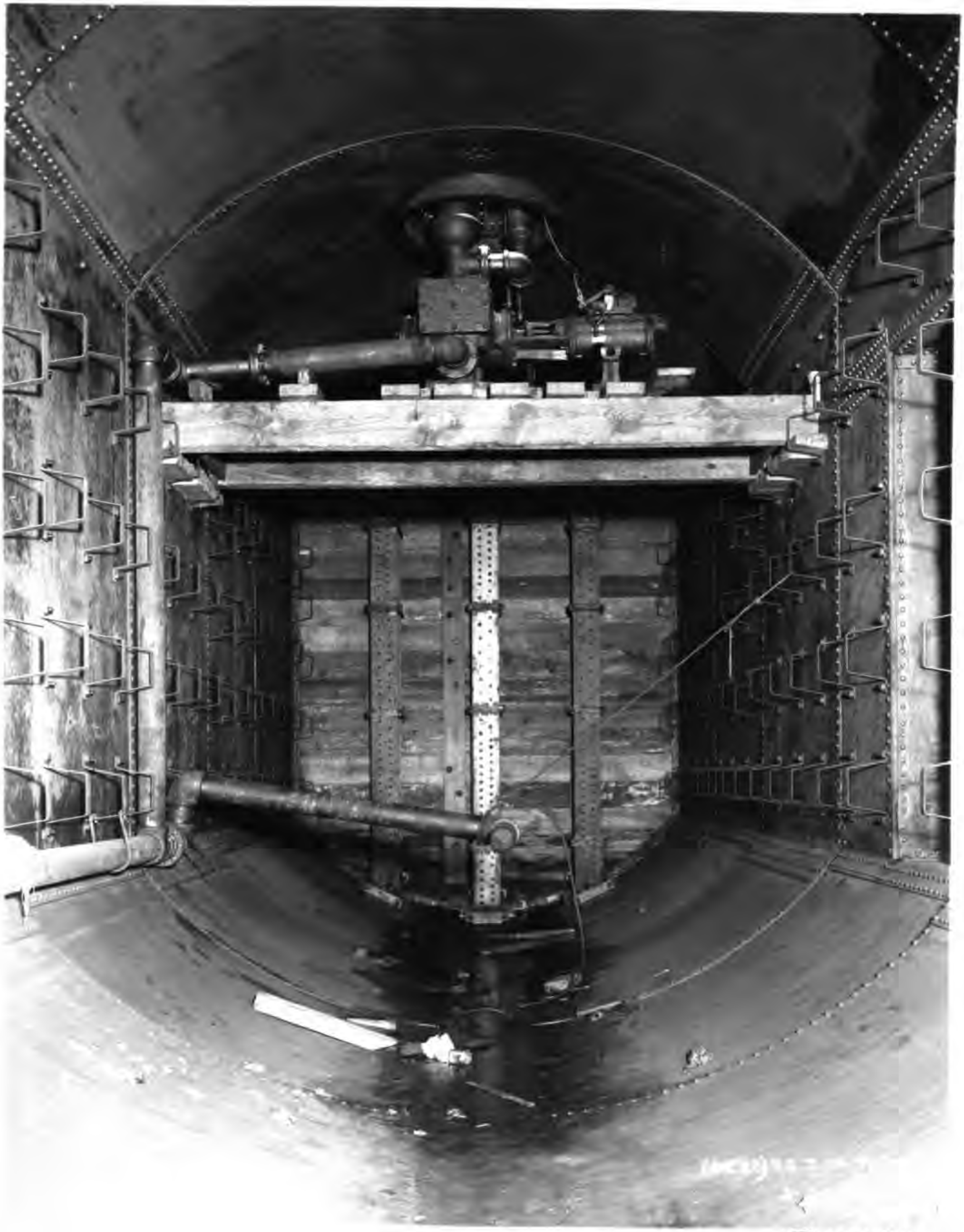


Figure 27

Cameron pump placed in the north end of Section "D" for unwatering the tubes. Also shows an interior view of the north bulkhead in one of the interior tubes of the Section.

of the diaphragms. The shafts were pumped out by means of small electrically driven centrifugal pumps and the Cameron pump which had been placed in the Section and lowered with it, was then connected and put into operation. This pump which was supported on a platform in the upper part of the tube directly beneath the shaft as shown in Figure 27, was started under water and operated until the surface was lowered sufficiently for the placing of additional pumps. For two of the tubes, pulsometer pumps with 4-inch discharge pipes were used and for the other tubes, a centrifugal and a Cameron pump having 4 and 6-inch discharge pipes respectively were installed. The total quanity of water in the four Sections which it was necessary to pump out against a head varying from 35 to 60 feet, was 5,500,000 gallons which was accomplished in about 12 working days.

All of the water was not removed from the tubes as soon as it could have been as it was found that there was from 6 inches to 2 feet of silt along the invert which it was possible to remove by pumping when mixed with plenty of water. The interior surfaces of the tubes were scrubbed and washed down with clear water and whatever silt and other material there waswhich could not be pumped, was wheeled to the shafts and removed. This accumulation of silt could have been almost entirely eliminated as was later demonstrated in Section E , by the placing of light wooden bulkheads in all four tubes and would have proved to be an economical addition to their equipment.

There were a number of small leaks where the nuts on the stay bolts between the interior walls were not sufficiently tightened previous to sinking. These leaks were readily stopped by tightening the nuts and the only other leaks noted at the time of unwater-

ing, were slight ones at the junction points where the water came through the exterior concrete and a very few places where the caulking at the laps was not perfect. The leaks at the junctions were effectively stopped by bolting plates to the zees which were riveted to the inside periphery at the end of each Section, and by means of wooden and in some cases rubber gaskets, the leakage was confined to the small void between the junction plate and the exterior concrete and was relieved by drain pipes through which grout was later forced in order to make it water tight. For details of this connection see Figures 9, 18 and 30.

Shortly after the tubes were unwatered one of the invert plates was found to have bulged inward about 4 inches from its normal position and caused some anxiety regarding its probable cause and more especially because the defect, developing after the unwatering, raised the question of the strength of the steel shell under pressure. A hole was drilled through the shell and the water pressure relieved and gradually reduced until only a small but constant amount of water was discharged. Later several bulges developed at various points in the structure and all of them in the same relative location, being about midway between the low point in the invert and the point where the invert and sidewall plates are joined. The bulges in no case extended for more than one half a diaphragm length, due no doubt to the exterior stiffening angle at the mid-point, but aside from the distortion in these plates there was no indication that the tubes were not in exactly as good condition as before the lowering.

By tapping on the shell plates with a hammer it was possible to determine areas over which the exterior concrete was not in contact with the steel, a condition which was so general through-

out that holes were drilled.through the steel plates, tapped and fitted with 1-inch grout pipes in preparation for filling these voids. At least two such pipes were placed between each pair of diaphragms and were later extended through the concrete invert, the grouting being deferred until after the invert was placed,in order to take advantage of this weight in preventing any bulging of the shell plates due to the combined water and grouting pressure. The limited investigation possible through these small grout holes developed the general information that while these areas were extensive, the space between the exterior concrete and the steel shell was not more than 1-inch except at the bulges and generally from ¼ to ½ an inch. The subsequent grouting into these voids has verified these observations and very little grout could be forced into them averaging ½ a cubic foot per lineal foot of tube including the grouting of the bulged areas. Realizing that the placing of the inverts would do a great deal to reduce the possible number of bulges, it was decided to place this portion of the lining at once. It was during the progress of this work that the first and only real set back occured.

Referring to Figure 2,it will be noted that sumps are provided at the low point in the profile to collect whatever leakage there might be in the tubes and portions of the approaches. There are two such sumps,one draining the easterly pair of tubes and one the westerly pair. Although the tubes had been cleaned and examined for structural defects, the sumps had been in continuous service collecting the leakage from the junctions, end bulkheads, bleeder pipes etc. and had never been entirely cleaned out or examined, so that it is not known whether the condition of the failure of the westerly invert joint of the west sump,was the result of the Sect-

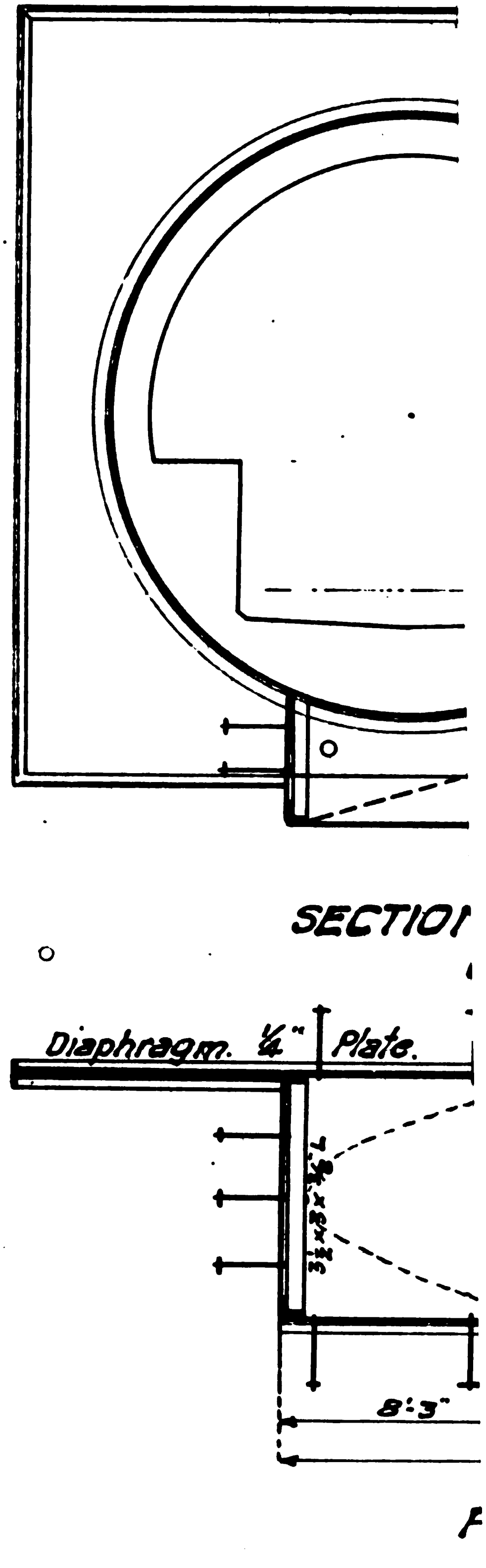


Figure 28

tion or determination of the failure could be made on account of

ion, while stored in the contractors "slip" previous to sinking, going aground and resting upon a submerged timber or pile at extreme low tide, or whether this joint was structurally weak and unable to withstand the external pressure.

Reference to Figure 28 may be made in noting that with the exception of the side which was formed by the lower portion of a diaphragm, the sumps were made of 3/8 inch steel plates with light angles riveted inside to reinforce the laps at the joints and that the walls of the sump were strengthened by 1-inch anchor bolts extending 2 feet into the exterior concrete. The fact that the lighter diaphragm plate was buckled about 2 inches from its normal position and at the top line of anchor bolts without producing any apparent movement or strain in these bolts, and that the failure occured at a joint which should have been the strongest section of the invert reinforced as it was, are probably the most logical contentions in support of the theory that there was at least a partial failure of this joint before the lowering of the Section into place. The bulging of the invert plates must give some credence to the belief that the water pressure was sufficient to cause the failure of what may have been a defective joint. In any event the joint failed and whereas the invert was built with a concave surface, in its distorted condition it was convex, the total movement at the center line of the sump being 2 feet. Figure 28 shows the extent of this distortion. The reinforcing angle at the joint, was bent to a contour corresponding with the plates and was found to be in good condition structurally although the heads had been sheared from all of the rivets which held it and the plates together.

The leak developed at night and no very extensive investigation or determination of the failure could be made on account of

the rapidly rising water and the accumulation of silt and sand which had never been removed in addition to the large quanity of fine sand which flowed in with the water, but it was evident that some portion of the sump had failed and that it would be necessary to put air pressure in the tubes in order to stop the leak and repair the sump. Anticipating such a contingency the end bulkheads had fortunately been built to withstand an outward as well as an inward pressure and a compressed air plant was at the time in operation supplying compressed air to a machine for the mixing and placing of concrete (to be described later), so that it was a comparatively simple matter to place air locks on two of the tubes and seal the other two with the circular plates which were used to cover the shafts when Section D was being lowered, and gradually increase the pressure until the leakage was stopped. Although there was some show of air at the junctions and at the ends it was not considerable and could have been readily reduced by caulking if it had been necessary to do so. The pressure was raised and maintained at about 24 pounds which was 3 pounds less than the theoretical pressure at the bottom of the sump. Wooden bulkheads were built in the two cross passages connecting the center pair of tubes so that no water got into the easterly pair of tunnels and when the air pressure was raised sufficiently, the water was exhausted from the two westerly tubes and preparations made to repair the sump. A framework of heavy timbers was placed in a manner to distribute over the inside top of the structure, the reaction from three 25-ton jacks which were used to gradually bend these invert plates back to their normal position. The operation was particularily successful at the joint where the original condition was obtained and the lapped plates covered with a 12" x $\frac{1}{4}$" plate attached by means of

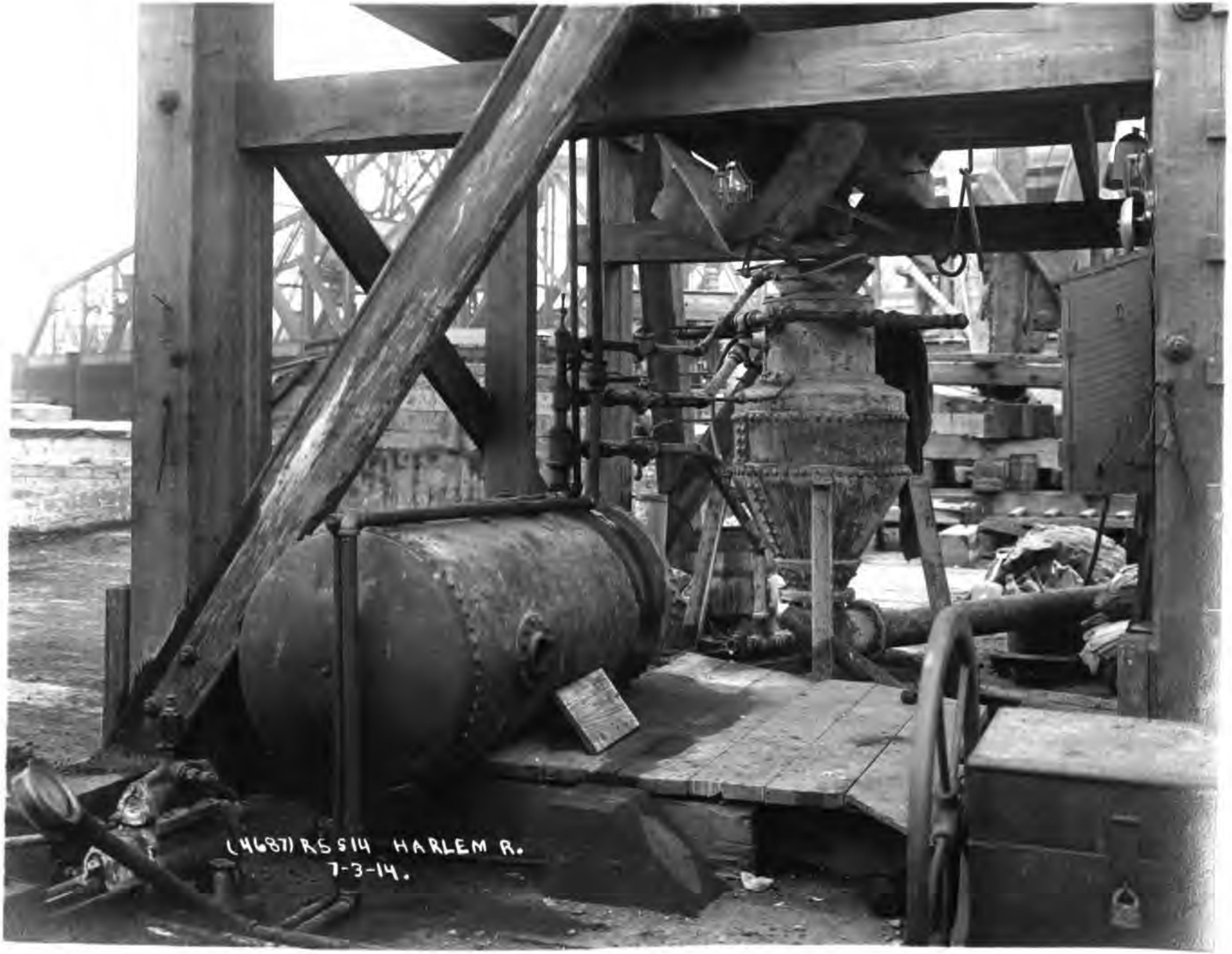


Figure 29

Pneumatic mixer for the mixing and placing of concrete.

stud bolts. In order to eliminate further concern regarding the strength of these sumps, both of them were lined with reinforced concrete before the air pressure was released.

PLACING OF CONCRETE LINING.

The placing of the reinforced concrete lining and the completion of the tunnel structure, developed some of the limitations of a new method and the dependability of an old one for the mixing and placing of concrete. The first method used was a comparatively new one by the use of compressed air and which is said to have given good results on other work and possibly under different conditions but which in its application to this work, proved to be expensive and entirely unsatisfactory. The essential parts of the equipment are shown in Figure 29 and consist of an air reciever and an ingredient chamber connected as shown, with a discharge pipe leading from the bottom of the chamber to the point of placing. In its operation the gravel, sand, cement and water in their correct proportions were let into the chamber from above and after clearing the rubber gasket around the entrance of cement, sand or other particles by a couple of blasts obtained by manipulating the valve in the upper pipe, a trap door in the top of the chamber was closed and air pressure applied to the contents for a few seconds, followed by the opening of the bottom pipe valve,admitting the air in direct line with the discharge pipe. As fast as the materials were forced down by the air in the top of the chamber and by gravity, they were shot through this pipe and discharged with considerable force into the forms. The capacity of the machine without any interruptions, was from 6 to 10 cubic yards per hour and was rarely equaled or maintained for any definite period.

It was contended by the owners of this machine, that at least one bend was necessary for its successful operation and that the long drop at the shaft was a positive advantage. Also that the concrete would be sufficiently mixed in passing through the pipe and being delivered with such force, would make a very dense concrete and be especially adaptable where a comparatively thin lining was to be placed and where tamping would be difficult. The plant was given a rather extensive try out and nearly all of the inverts in Sections A, B, C and D were placed by this method. At times the operation was quite satisfactory especially where the point of placing was less than 400 feet away, but at all times there were delays due to the blocking of the pipe especially at the bend at the bottom of the shaft. From the machine the discharge pipe was horizontal forabout 35 feet and turned down the shaft for a 45 foot drop and with another right angle sweep the pipe continued practically horizontal to the point of placing and straight except when working in the adjacent tube when two more right angle turns were required. As has been previously stated, most of the trouble was occasioned by blocks at or near the shaft and may perhaps be accounted for by the fact that the materials which left the machine first, while mixed to a certain extent with air, did not have the full line pressure on account of the rapid expansion of the air in filling the pipe, and the materials fell to the bottom of the shaft with such momentum as to form a plug, which unless the pressure was sufficient to break down at once became more compacted and effectively blocked the pipe. It is certain that when these blocks occured the pipes were cleared in most cases with considerable loss of time and seriously interrupted concreting operations. When the mixer was working satisfactorily, a rather wet but appar-

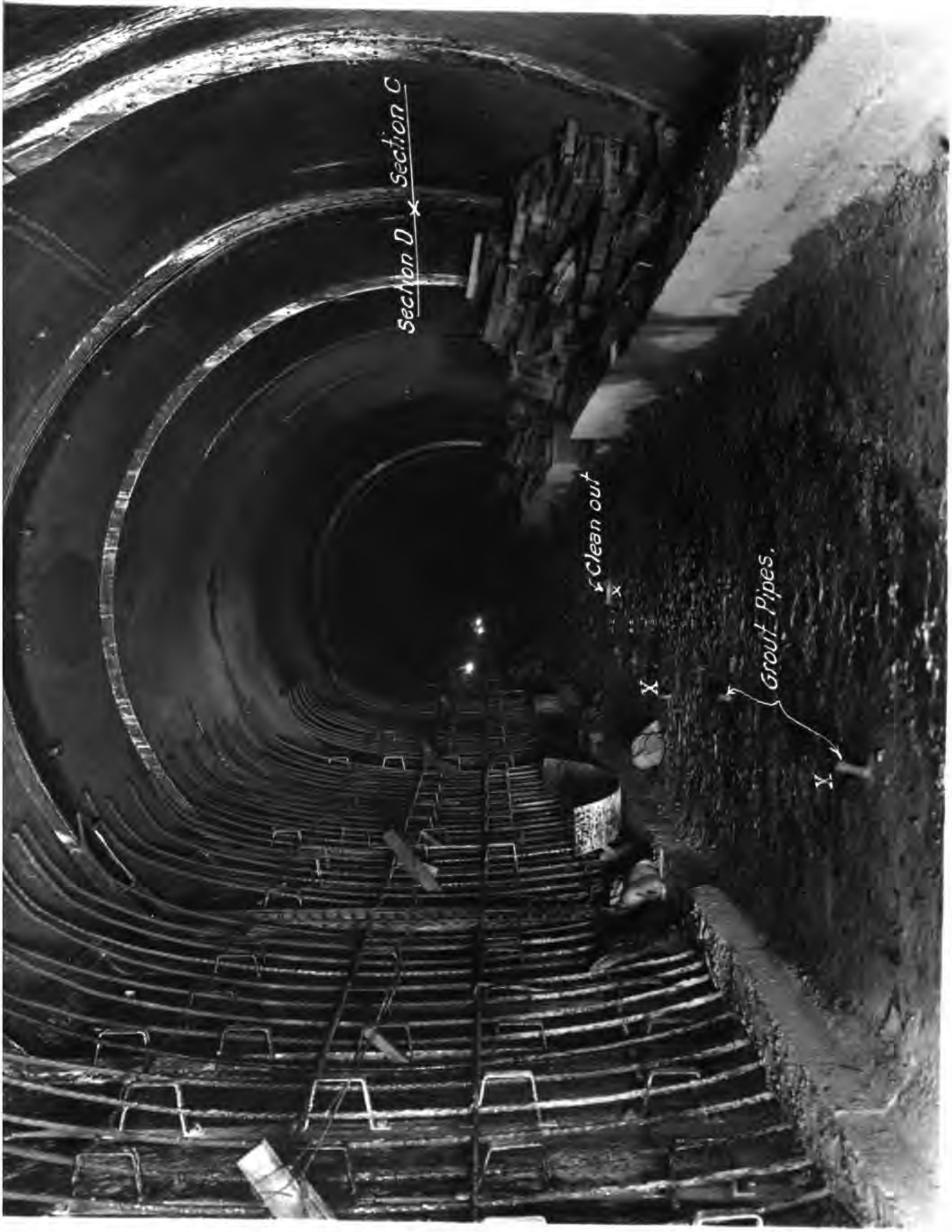


Figure 30

ished invert was used to support wooden ribs spaced about 3 fe

Concrete invert completed near the junction of Sections "C" and "D" and showing a view of this junction. The interior angles in the fore ground represent the former position of the end bulkheads and the one in the distant was at the upper semi-bulkhead.

ently well mixed concrete resulted but generally the gravel was shot out with considerable velocity accompanied by a spray of finer particles while the most of the mortar poured out of the pipe under no apparent pressure and dropped into the forms. The result was that all of the concrete had to be worked over in the forms which fortunately was possible in the inverts. The only real function that the plant served was to transport the materials in the proper proportions and deposit them in the forms for mixing. The total cost of placing the concrete by this method including the air was about $4.00 per cubic yard.

Before the invert concrete was placed all of the sidewall reinforcing rods (which by refering to Figures 3 and 30 will be seen to extend into this concrete) were tied with wire to the anchor straps and to the longitudinal rods. Discharge pipes leading from the sumps through the inverts in each tube were assembled upon concrete wedge-shaped piers and concreted in place. Extra heavy cast iron (Universal) pipe was used, with clean-outs marked "x" in Figure 30 provided about every 100 feet, and these pipes were connected with the sewers on both sides of the River. Provision was made by valves and by pipe connections between the sumps, to enable either of the pumps which will be permanently installed in the tubes, to drain either sump or both of them if necessary or, in event that both of the pumps should be out of commission, connections were placed to attach a pump-car to serve the same purpose.

The arches and sidewalls (except for the duct benches) were placed in one continuous operation in sections 30 feet long. A wooden framed traveler running on light rails placed upon the finished invert was used to support wooden ribs spaced about 3 feet

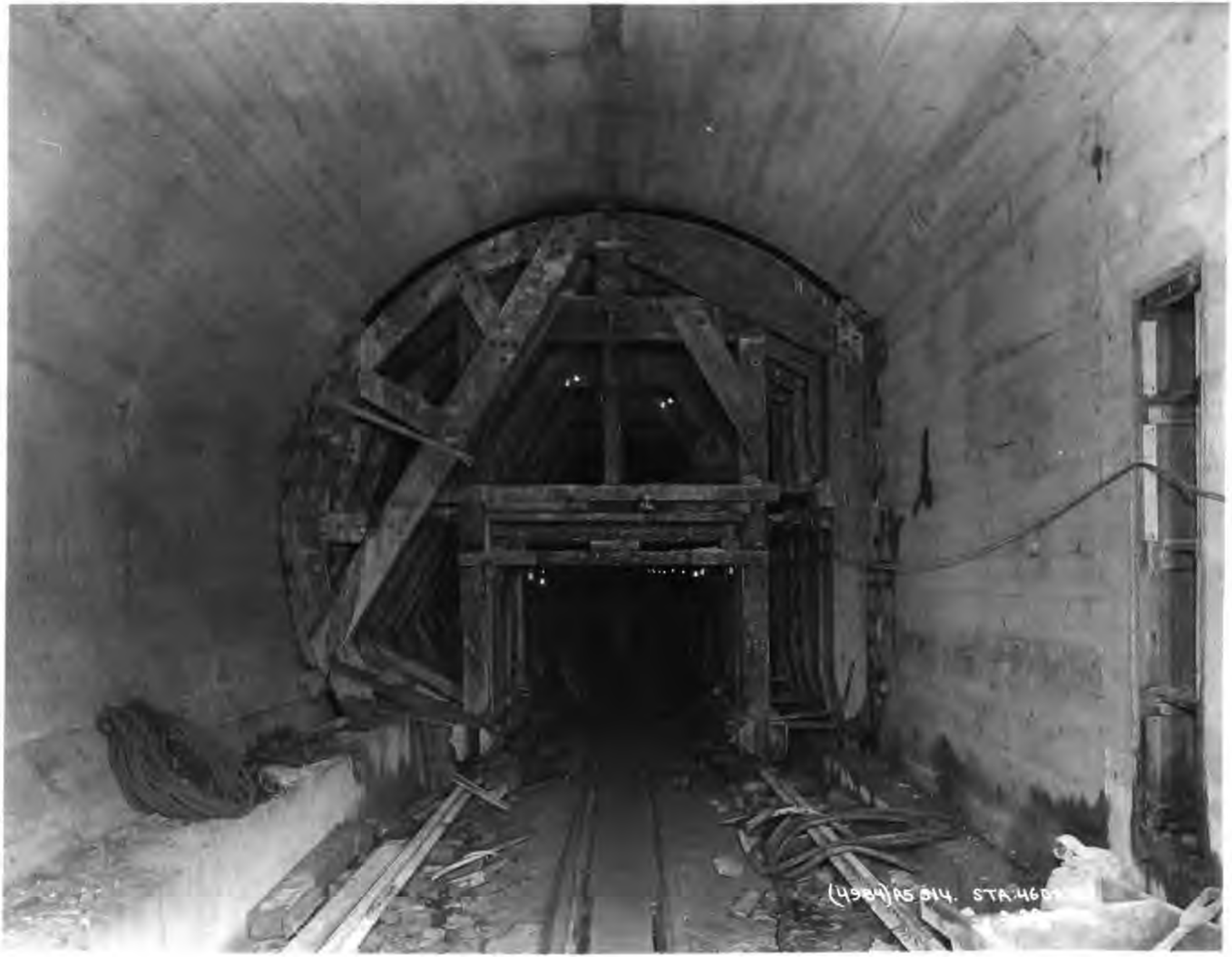


Figure 31

Conrete lining completed with the exception of the duct benches. The forms are all set and ready for the placing of the next section. A cross passage is shown on the extreme right with the forms in place.

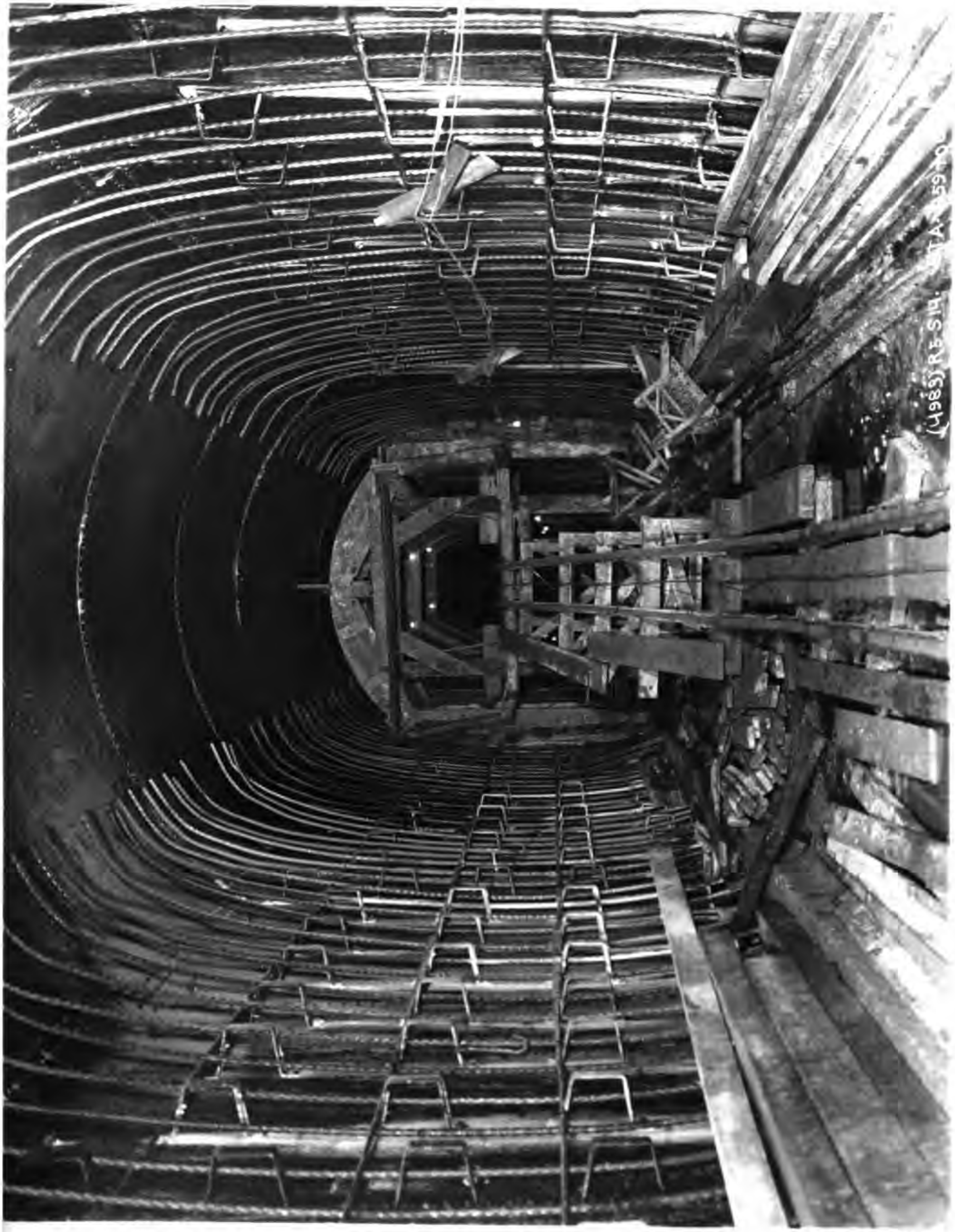


Figure 32

Forms set for concreting in one of inner tubes showing view of reinforcing rods and method of secureing them.

on centers to which 2-inch wooden lagging was fastened. The traveler was wedged up clear of the rails when the forms were set and the ribs were blocked upon the concrete previously placed, making rigid forms which could be collapsed sufficiently to remove the lagging by taking the blocking and wedges out. Figure 31 shows the traveler and forms set up in one of the outside tubes with the sidewall lagging in place. The concrete was mixed by a rotary batch mixer and dropped down a vertical chute into a hopper from which it was loaded into small dump cars operated in 3-car trains. These cars were hauled up the incline shown in Figure 32 and dumped upon a platform from which the concrete was shoveled into the forms and worked over as much as possible with long tampers. Enough water was used in the concrete to make it flow readily and by pounding on the forms with a wooden maul, a satisfactory surface was usually obtained.

As a further demonstration of the pneumatic mixer, a 20 foot section of arch and sidewall was placed. When the forms were removed portions of the work had a very satisfactory appearance while other portions showed streaks of aggregate with very little mortar incorporated. In many of these places where the surface finish was good it was found that there was only a thin coating of mortar which when removed exposed poor concrete. It was therefore necessary to cut out all of this concrete for no complete section was good throughout and the lack of mortar in the honeycombed concrete provided an excess of it in other portions, making it difficult to remove especially in the sidewalls on account of the reinforcing rods and anchor straps. It is hardly necessary to add that the pneumatic method was discarded in favor of the one described which

has given uniform and satisfactory results. The average cost of placing this lining including the cost of forms and overhead charges was $4.00 per cubic yard.

Anticipating that the concrete arch would settle away from the steelwork somewhat, grout pipes were placed every 15 feet on the average, extending through the arch lining and to within ¼ or ½ an inch of the shell plate. These pipes and the ones previously referred to which lead to the outside of the steel invert, marked "X" in Figure 30, were all filled with neat cement grout under a line pressure of 90 to 100 pounds using the familiar type of grouting machine shown in Figure 33. An average of 2 cubic feet per lineal foot was placed between the steel and arch lining (i.e. in the top pipes) and as previously stated, an average of ½ a cubic foot per lineal foot of tube was forced outside of the steel shell in the invert. Under these conditions it seems fair to assume that both sides of the steel shell are well supported and protected and in direct contact with concrete or grout.

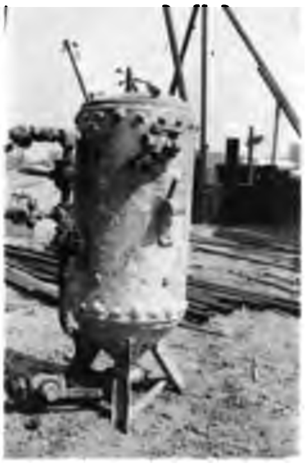
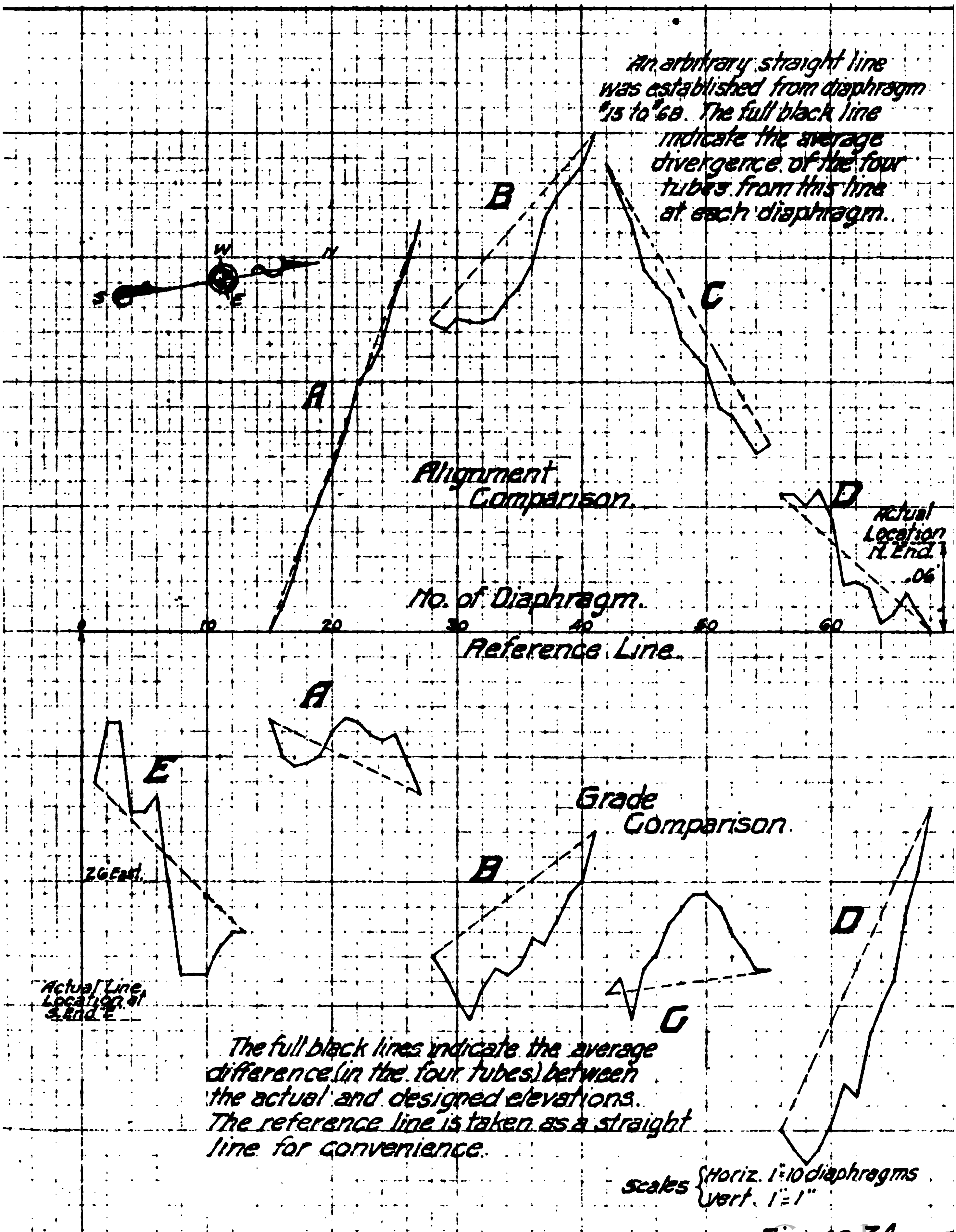


Figure 33.

The laying of the ducts for the power and signal cables and the completion of the concrete duct benches developed nothing of special interest. One-way ducts with asphalt wraps at the joints were used throughout and in no case was there any difficulty in rodding them. Splicing chambers were provided at intervals of about 330 feet along the outside walls of the outer tubes, a partial view of one of them appearing in Figure 35. Cross passages are placed about every 50 feet in the division walls between the



Alignment Comparison.

An arbitrary straight line was established from diaphragm #15 to #68. The full black line indicate the average divergence of the four tubes from this line at each diaphragm.

Grade Comparison.

The full black lines indicate the average difference (in the four tubes) between the actual and designed elevations. The reference line is taken as a straight line for convenience.

Scales {Horiz. 1" = 10 diaphragms
Vert. 1" = 1"

Figure 34

outer pair of tubes with refuge niches between for the additional safety and convenience of the workmen. There are but two cross passages between the center pair of tubes, one near each end, but refuge niches were placed throughout the length of this wall opposite the crosspassages in the outside division walls.

GENERAL SUCCESS OF THE METHOD.

Throughout the prosecution of the work the prevailing idea of the contractor was to get the best results possible and this commendable spirit extended throughout their organization. The outcome has been most satisfactory for so far as is known, there is not a single defect in the structure effecting its safety or utility. Figure 34 was prepared to show something of the actual condition of the steel tubes after they were unwatered. To get an idea of the divergence of the four Sections from a straight line, an arbitrary reference line was established between the last accessible diaphragm in the south end of Section A and in the north end of Section D and readings taken at each diaphragm and plotted to a full vertical. The maximum divergence from this line was 4 inches at the north end of Section B and the maximum deviation from a straight line of any individual Section, was ½ an inch, Section A being almost perfect. Section E could not be included in this record on account of the conditions on the work. A comparison of the actual and the theoretical elevations of the tubes, is shown by a line of rather more irregular contour having a maximum difference of 4¼ inches and a maximum divergence from a straight line from end to end at the bottom of 7/8 of an inch. An interesting and very uniform condition is the difference of 1 3/8 inches at each of the junctions A-B, B-C and C-D and the slightly greater one of 1¾ inches at E-A. No very positive reason can be given for this, ex-

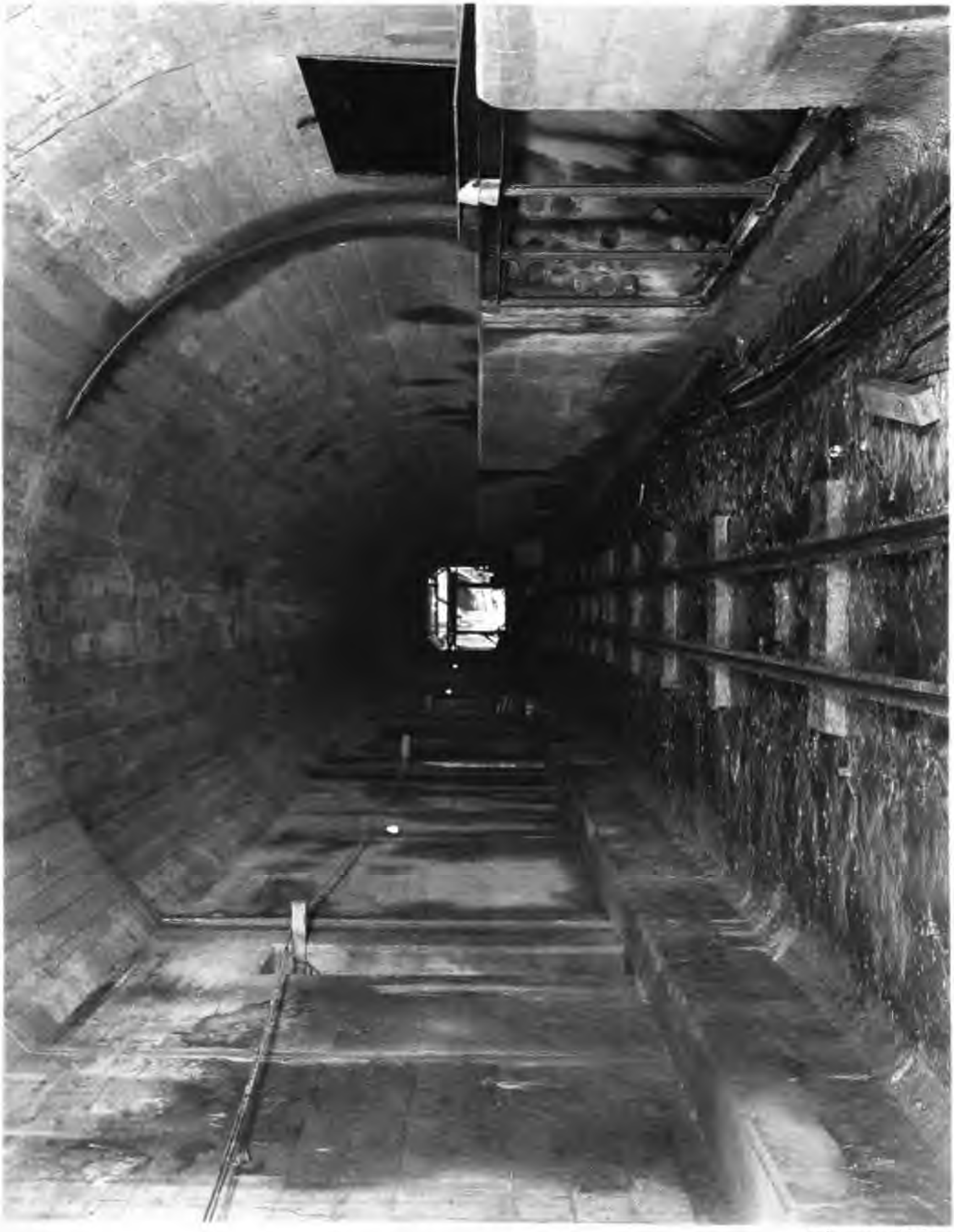


Figure 35

[illegible]

Bronx end. The tunnel consists of two intersecting cast iron

View of the completed work in one of the outside tubes. The Splicing Chamber shown at the right will be walled up in front with an asbestos covering.

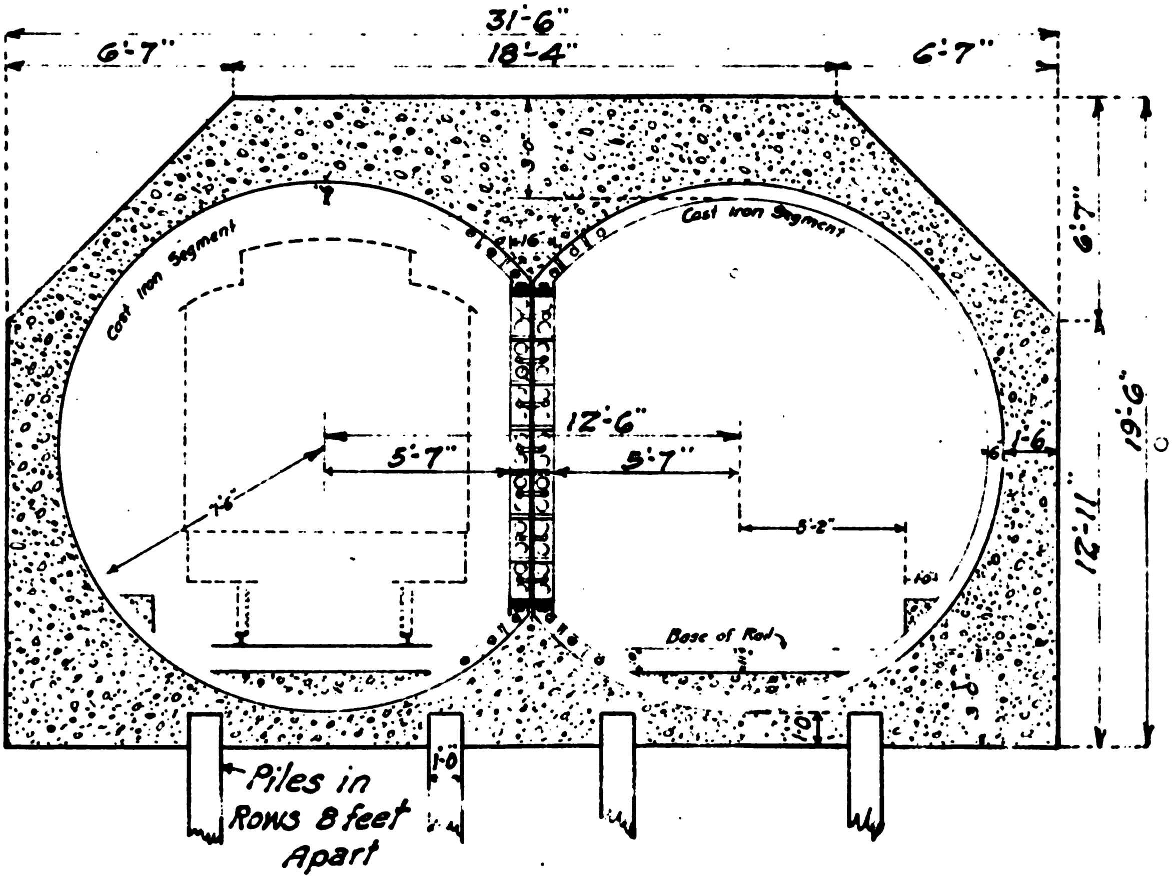
cept a possible elongation of the outside tubes in a vertical plane due to the weight which was placed upon the 5-inch pin connections attached to these Sections at the top. However when it is considered that these small variations from the theoretical lines have resulted from the accumulation of shop and erection errors as well as construction methods, it must be granted to be rather remarkable for a structure of its dimensions, built of light shapes and plates and located entirely from the surface with the assistance of divers.

The sequence of operations was well planed and so carefully executed that there were comparatively few accidents and no fatalities. Many interesting details were originated which taken together contributed to the interest and success of the project but which could not be covered in this treatise. It is not necessary to go beyond the fact in stating that at the present time these tubes have a smaller proportional leakage than any other railroad tunnel in New York City and give every indication of being the most economical and satisfactory type so far proposed, adaptable to the conditions met with in the Harlem River. Figure 35 shows an interior view of the completed tunnel ready for track and equipment.

METHOD USED ON FIRST CROSSING OF HARLEM RIVER.

Preliminary to any comparison of the two methods used in crossing the Harlem River, it is necessary to have in mind the essentials of the first crossing by the West Farms branch of the Lenox Avenue subway now in operation.

The tube portionof this crossing has a length of 641 feet, projecting 90 feet inland on the Manhattan end and 140 feet on the Bronx end. The tunnel consists of two intersecting cast iron



CROSS SECTION OF HARLEM RIVER TUNNEL.

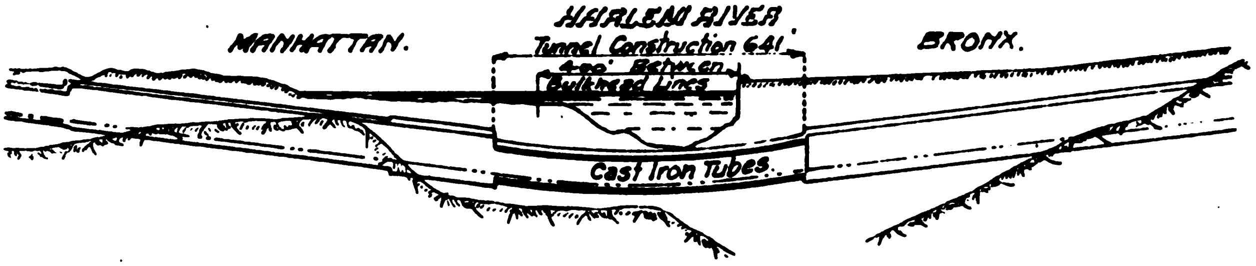
Figure 36

cylinders having an external diameter of 16 feet with their axes 12 feet and 6 inches apart and separated by a vertical diaphragm of cast iron segments. The tunnel is made up of rings 6 feet long composed of several segments bolted together through their inside flanges and in the finished structure, are embedded in a rectangular mass of concrete with the upper corners cut off on an angle of 45° (Figure 36). The River has a maximum depth at high tide of 26 feet and the lowest point of the invert is 48 feet below mean high water. In order not to interfere with traffic on the River it was permissable to block only one half of the channel at one time, which naturally suggested building the tunnel in halves.

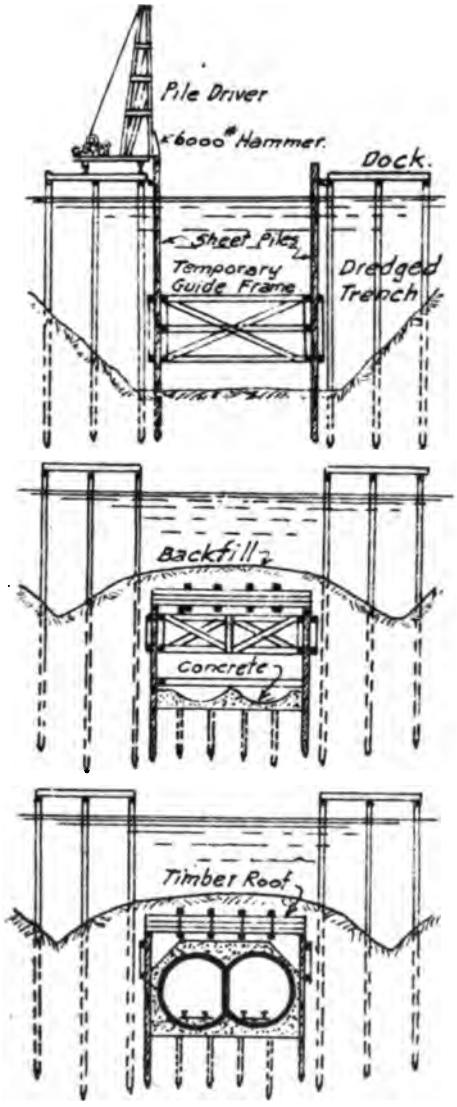
The first half from the west shore to the middle of the River, was built under pneumatic pressure in a caisson formed in a dredged trench, by driving and bracing 12"x 12" sheet piling to form the walls and covering them with a solid timber deck or roof platform sunk into place and resting upon the top of this sheeting. Underneath this roof the excavation was completed, the cast iron shell assembled and the concrete lining placed, all under an air pressure reaching a maximum of 14 pounds above atmospheric. While studying the possibilities of an economical modification of the system, a plan was evolved which consisted of the substitution of the upper half of the permanent iron and concrete tunnel structure for the timber roof. This second method was used under the east half of the River. Figure 37 shows the essentials of both methods which will now be briefly described.

DETAILS OF METHODS.

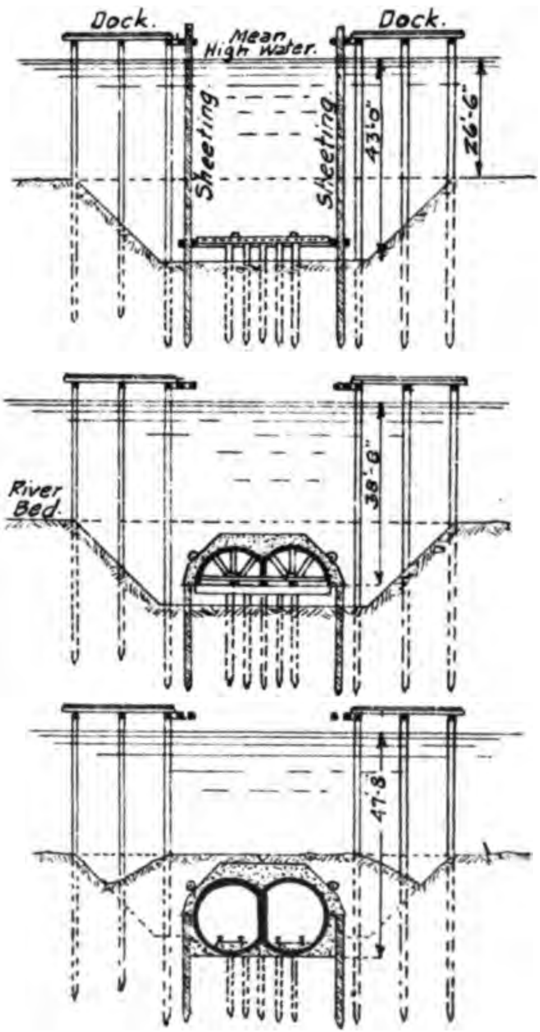
The first proceedure in both of the methods after dredging, was to build docks about 20 feet wide for the length of the contemplated section of work and along both sides as shown in Figure 37.



PROFILE OF HARLEM RIVER TUNNEL.



METHOD USED
FOR WEST HALF.



METHOD USED
FOR EAST HALF.

Figure 37

Timber piles in rows 8 feet apart and four piles in a row, were then driven to support a temporary horizontal frame which was submerged and served as an alignment guide for driving the sheet piling. This sheeting was of special construction consisting of three 12" x 12" timbers 65 feet long, planed on all sides and bolted together with a tongue and groove formed by 4" x 3" strips fastened to the edges. In order to assure accuracy in driving these piles and to detect the presence of boulders or other obstacles that might be encountered, a set of four steel pilot piles 60 feet long were first driven adjacent to the last wooden pile. Three of them were then withdrawn leaving a space into which the wooden pile was placed and driven to a somewhat greater depth. The piles were braced and then cut under water to the grade of the underside of the timber roof. This roof was made of three layers of 12" x 12" timbers bolted together and when it was weighted and sunk upon the side sheeting, backfill was placed upon it to the original River bed which completed the preparation of the working chamber. As the water was exhausted the air pressure was increased until workmen could get in and remove the excavation. The invert piles were cut off to embed their tops in the concrete foundation and in proper sequence the concrete and iron lining with its protecting encasement of concrete, was placed completing the structure.

The second method was the same as the first up to the point of cutting off the side sheeting which was made at the elevation of the axes of the tunnel. Then a pontoon 35 feet wide, 106 feet long and 12 feet deep, was built over the center line of the tunnel and the upper half of the cast iron structure assembled upon and secured to, a watertight floor laid upon this pontoon. This temporary floor was braced against upward pressure and the arch

segments were held in position by the use of timber struts and tie rods. The ends of the roof structure were closed by transverse ¼" diaphragm plates bolted between the flanges of the last two rings. The exterior concrete was then placed, practically completing the upper part of the tunnel. On account of the vertical curve, the tunnel was built in sections about 90 feet long and as fast as they were completed they were lowered into position.

The process of lowering consisted of admitting water to the pontoon and loading it with enough sand to gradually sink it, at the same time accomplishing the launching of the roof structure and permitting the pontoon to be pulled from beneath. Eight of the 60-foot steel pilot piles were uniformly distributed above the section to span between the working docks and before launching the roof structure, lines working in 4-part tackles, were attached to these temporary supports and to eye bolts embedded in the tunnel roof, so that as the pontoon settled away the structure was restrained from any uneven settlement. Each tackle was operated by one man who took one or more turns around the pile and slacked it as necessary, keeping the structure level according to vertical scales attached to the roof at various points and projecting above the water. The calculated weight of the cast iron, concrete and timber to be sunk was 50 pounds less per lineal foot than its total displacement and this buoyancy was overcome by placing a few loose stones upon the top of the structure. As the tunnel roof was being lowered, air of a pressure corresponding to the depth of submersion was kept in it, in order to decrease any possible leakage through and to equalize the pressure upon the false floor. Fine vertical wires were adjusted on the center line of the tunnel at each end and aligned with a transit, placing the tunnel in its

final position. With the section in place a diver went into the junction through an opening provided by the removal of a segment in the end ring of the section and boltedthis section to the one adjacent and then replaced the segment. The proceedure from this point did not differ materially from the first method as outlined. There was comparatively little difficulty in removing the excavation and the materials could be kept dry by an air pressure computed to the elevation of the axis of the tunnel, due largely to the depth of 18 feet or more that the side sheeting extended below sub-grade. The maximum pressure maintained was 14 pounds which was about 6 pounds less than that required for the hydrostatic head at the lowest point in the invert.

COMPARISON OF THE TWO TYPES OF TUNNELS.

Regarding the two river crossing projects from the standpoint of utility, a comparison of the cross sections of each is all that is necessary to note certain modifications in the ideas of lining tunnels as applied particularily to subways and which now require plenty of accomodation and protection for the power cables and some provision for the safety of workmen in the subway and for passengers in cases of emergency. The Harlem River Tubes have undisputed advantages in arrangement and in the addition of modern details, but these same advantages appear in type "L" Figure 1 which probably represents the modern adaption to this pioneer tunnel, so that these advantages are the result of experience in the requirements of such structures rather than any advantage of the method. Structurally both are without a doubt amply safe and depend for a comparison upon the relative merits of cast iron as against steel and reinforced concrete for sub-aqueous tunnel linings. It seems to be more generally admitted that a comparison of the relative life of steel and of cast iron when exposed as in water

or gas pipes, is in favor of cast iron. The question which naturally presents itself, is whether or not the exterior concrete will have silted up or become impervious to infiltration before the steel has lost its properties of resistance, by chemical action or other agencies, or whether the steel shell and ultimately the reinforcing rods will not deteriorate and cause the Tubes to loose their waterproofness and perhaps reduce their factor of safety. Considered strictly on the basis of present conditions and the utility of each as subway tunnels, the Harlem River Tubes are undoubtedly more nearly damp-proof and generally more satisfactory. The contention that they will deteriorate in time is not susceptible of proof at present, so that the serious resulting consequences of such a condition and one which is involved in all sub-aqueous reinforced concrete construction, is in no way conclusive against the method.

The main advantage gained by the Harlem River Tube method was the elimination of the necessity for using compressed air although they provided an absolutely safe working chamber in case of an emercency. The use of compressed air is always expensive and attended with more or less uncertainty and risk. In one instanee during the construction of the first Tunnels, it was found that owing to a defective air gauge the pressure had been raised to a point where it was theoretically able to lift the roof from the side sheeting . The Tubes interfered very little with the river traffic as no docks were required and whatever blocking of the channel was necessary, was only for a comparatively short time. Being made of light structural steel they were readily built true to design and could be checked before launching. The light

weight made it possible for a comparatively long Section to be handled without difficulty. The simplicity of plan together with the complete and easy control of all of the operations involved contributed largely to the success and advantages of this method.

A question which has caused some discussion and which still remains unsettled, relates to the condition of the exterior concrete deposited with the tremie. The exterior concrete on the roof of the first Tunnel crossing was placed out of any contact with water and leaves no reasonable doubt of its characteristics. The use of the tremie offers no opportunity for inspection of the results obtained, excepting the reports of divers and such samples as they may obtain . From investigations made it is certain that a portion of the cement is separated from the concrete but no accurate idea can be formed of the probable amount of it and most of the samples of concrete obtained show about the same general characteristics as would be expected in mixtures of the proportions used. A very safe and logical provision for tremie concrete which is expected to have strength requirements, is to materially increase the proportion of cement in the mortar and decrease the amount of large aggregate. In other words it would appear that a tremie deposit of 1:2:4 or 1:2½:5 might be expected to give a resulting concrete of the proportions 1:3:6. However as the exterior concrete in the case of the Tubes served to weigh the tunnels down and hold them in position, the question of its strength was not material except as it influenced the density which it was desireable to have for the protection of the steelwork. No investigations have been made as yet which have disclosed any unsatisfactory concrete, but the leaks at the junctions and the general condition

of water pressure adjacent to the shell plates, make it seem very probable that a denser concrete could have been specified to advantage.

In all probability the fairest comparison of the relative costs of the two methods for the same number of tubes is given in the bids for the types "L" and "K" made at the time of the letting of the contract for the Tubes. The price per lineal foot of $1425 for type "L" and $1500 for type "K" would seem to indicate that the original tunnel was more economical as modified and enlarged, but without knowing something more definite about the relative costs it seems fair to assume that there is very little choice between them in this regard.

GENERAL ADAPTABILITY AND LIMITATIONS OF THE HARLEM RIVER TUBE TYPE.

This type and the first tunnel under the Harlem River have much in common in their application to sub-aqueous tunnels under comparatively shallow streams. For the best conditions to obtain, the structure should be almost if not entirely below the bottom of the River in order to prevent any undermining of the foundation or a possible injury to the structure from the sinking of a large boat upon its roof. The necessity of the almost constant use and dependence upon divers, places the greatest distance of the invert below water at the practical diving limit which for steady work would probably be about 75 feet. Conditions of current are controlling features which are of considerable moment in the operation of lowering and of anchoring a Section, and the maximum conditions permissible with safety would depend entirely upon the anchorages obtainable. In very shallow streams or rivers the elevation of the top of the tunnel can be brought to the highest possible limits

permitted by the requirements of navigation, thus making the approach grades much less than they could be with the shield method. This conduces to economy both in operation and in maintenance and simplifies greatly the question of drainage because it reduces the pressures under which water would find its way into the tunnel. In soft ground, piles may be driven and cut off to grade and used to support the structure. There are various features of arrangement and design which effect great economies over the shield method especially in regard to the cross section. The form is not restricted to a circular form and a tunnel may be built of two or more tracks without increasing the height or depth of the structure and with a minimum of waste space. In short these Tubes have an advantageous and satisfactory application to sub-aqueous crossings where the depth of water is not more than 50 feet and where ordinary or shield tunneling methods do not suffice or seem expedient.

Approved Edwin T. Holden

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